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KEY TECHNOLOGY CENTERS' SURVEY OF SUPERCONDUCTIVITY FIELD

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Report on Superconductivity Field by Japan Key Technology Center

916C0006 Tokyo CHODENDO BUNYA NI KANSURU CHOSA HOKOKUSHO in Japanese Mar 90 pp 1-97

[Text] **Foreword**

It has been only three years or so since the end of 1986 when conductors of oxides that conduct current at high temperatures were discovered. Since then, the field has seen remarkable growth, as evidenced by the discoveries of compound copper oxides of yttrium, bismuth, and thallium, and by epochal improvements in critical temperature and critical pressure. The progress of technical development during this period can be said to equal the cumulative achievements of metal superconductor research and development of the past 80 years. The current industrial emphasis seems to be shifting away from the race to realize criticality at higher and higher temperatures and toward the manufacturing and machining technology of high-temperature superconductors for practical applications. Manufacturing and processing technology development is where Japan is strongest, but active research in this technology is being promoted in China and India. The manufacturing and machining technology of high-temperature superconductors, a bridge to the science and technology of the 21st century, is a fundamental technology in which Japan could never allow itself to play second fiddle.

In light of this situation, the Key Technology Center undertook a three-year survey beginning in FY 87 entitled "A Survey of the Superconductor Field." The purpose of the survey was to accurately grasp the latest movements surrounding high-temperature superconductivity, extract the technical tasks associated with the technology's practical use, and analyze the technology's impact on industry, thereby promoting future R&D in the field.

The objectives of this year's survey were 1) to grasp the latest movements surrounding the development of high-temperature superconductors of oxides on the strength of the achievements obtained in the course of the survey and research activities in FY 87 and FY 88; 2) to extract the technical tasks that must be overcome before superconductors can be put to practical application and clarify the measures for overcoming the tasks; and 3) to survey and analyze the impact the technology will have on industry and obtain the basic data necessary to promote the key technology.

The results are put together in this report under the categories of the potential for growth of the technology as an industry, the priority tasks for technical development in the future and their prospects, and the superconductor R&D tasks from the corporate side. This report also contains the latest movements in Japan and other countries in patent applications.

This series of surveying activities has been completed with the current survey in FY 89, and it is hoped this report will provide useful basic data on the superconductor field and will facilitate the testing and research on the key technology as well as help draft the policies for promoting the technology.

We would like to express our sincere thanks for their help to the International Superconductivity Industry Technology Research Center that undertook this series of surveys under contract, to the members of the Superconductivity Survey Committee and members of the Expert Committee, and to the concerned people in the Ministry of International Trade and Industry.

March 1989
Key Technology Center

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Japan Key Technology Center

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Chapter 1. Introduction

More than three years have passed since the end of 1986 when the existence of the first high-temperature superconductor was confirmed. Anticipating the great impact the discovery will have on the industrial society, this series of surveys was started in early FY 87 and has terminated with the completion of the current survey for FY 89.

With the discoveries of new superconducting materials one after another and their increasing transition temperatures as its background, the survey in the first fiscal year (1987) was mostly aimed at sorting the new materials and their basic properties. A survey was also made of the concern for a stable supply of raw materials. During the survey period, large increases were realized in the cross section, with the transition temperature rising from 40 K (December 1986) to 90 K (February 1987) to 110 K (January 1988) and still higher to 125 K (February 1988). The dream of superconductors using liquid nitrogen refrigerant was therefore realized. However, as for the great characteristic of superconductors conducting large currents with no loss, the prevailing view was pessimistic.

With these in mind, in the second-year survey (FY 88) the emphasis was on accurately grasping the rising transition temperatures and probing the trends of the rises in the superconducting temperature, as well as on the possibilities of applying superconductors to electronic devices. During the second-year survey, breakthroughs in the transition temperature were achieved one after another, and it was recognized that high-temperature superconductors could fully conduct large currents, provided they were used as small testpieces. The equation shifted to a question of manufacturing technology—could these superconductors be fabricated into large-size practical use-level wire materials while retaining their superior characteristics? As for superconductor-based electronic devices, the basic properties that are expected of high-temperature superconductor-based devices were clarified, and the difficulty of forming Josephson tunneling junctions when putting these devices to practical use was pointed out and concern was expressed of the higher noise levels of these devices.

In the third-year survey (FY 89), i.e., the current survey, emphasis was placed on sounding out the news of the Japanese industrial circles that had been engaged in superconductivity R&D on the future trends of metallic superconducting materials and high-temperature superconducting materials. At the same time they were asked in a questionnaire what role they expected the government and public research institutes to play in this respect. Copies of the questionnaire were sent to corporate people who were actually engaged in R&D and some were sent to experts in the governmental and academic circles.

Those people in charge of technical development are constantly buffeted with many difficult problems, and they are expected to solve all those problems on their own. The result is that in any questionnaire survey of research people on their prospects for success, often the answers tend to be pessimistic. In this context, we believe this questionnaire is valuable in that it represents the moderate estimates of the future potential of superconductors.

The questionnaire contained such questions as, "When will the various problems associated with materials be solved?" "When will these superconductors find applications in devices or systems?" "How will the market grow?" The people polled were also asked to supply concrete comments.

The questionnaire results supported the view that metallic superconductors, which are already in the takeoff stage, will find an increasing application in superconducting quantum interference device (SQUID) and magnetic resonance imaging (MRI) systems, but their market will be less than ¥400 billion by the year 2010, while commercialization of superconductor-based Josephson devices and three-terminal devices with a potential for larger markets is anticipated to start sometime around the year 2000. As for oxide superconductors, it is forecast that their application in SQUIDs will start in 1995 or sometime later, in Josephson devices in 2005 or sometime later, and in magnets after the year 2010 even for MRI, the device expected to incorporate superconductors ahead of other devices.

The expert forecasts that it will be a long time before systems incorporating oxide superconducting materials will find practical use are based on the thinking that given the utilities of the metallic superconducting materials using liquid helium as a coolant, oxide superconductors will see practical use only when their cost performances have surpassed those of metallic superconductors. That is, the experts forecast that metallic superconductors will continue to play a leading role in the field of superconductivity for the next 10 to 20 years.

Since the experts see that it will be 10 to 20 years before oxide superconductors find widespread commercial use, they seem to be bracing themselves for long years of R&D. Take the examples of recent years—carbon fibers, amorphous semiconductors, compound semiconductors, and liquid crystals; all were developed after long years of R&D. High-temperature superconducting materials must overcome many obstacles before they find widespread use, and consequently it is no wonder that the experts think the technology needs a long-term commitment.

As with the newly discovered materials, the conventional pattern of development—where a long-term R&D project toward a higher technological goal serendipitously hits upon a somewhat different application of the technology, providing a further incentive for research—will also apply in the R&D of high-temperature superconducting materials.

Full efforts will also have to be made on the metallic superconductors, which are expected to be the mainstay for the next 20 years or so, if only for their healthy growth.

Chapter 2. Prospects of Growth as an Industry and Principal Tasks

2.1 A Questionnaire

2.1.1 Objective of the Questionnaire

We (members of this surveying committee) sent copies of a questionnaire to 22 members of the Committee Proper and the Expert Committee to sound out their opinions on the growth potential of superconductivity as an industry (with respect to technical forecast and market scale) as well as on the tasks facing the technology. By tallying and analyzing these opinions, we intended to produce our own prospects for the growth of the technology.

2.1.2 Questions in the Questionnaire

The questionnaire was made up of the overall survey (R&D as seen from enterprises), the superconducting materials, and the application fields. Individual questions were as follows:

(1) Overall Survey

1) In connection with the key technologies for high-temperature superconductivity research, those fields or targets of research that are beyond the capacity of private industries.

2) Anticipated superconductivity-related projects (requests to the government and expectations for the roles of the government).

3) Projects for which R&D is desired to be implemented urgently.

4) Of the evaluation, testing, and large-scale equipment, those that are desired to be kept in the hands of the public organizations.

5) The desirable ways public or semipublic centers and research labs should be operated.

(2) Metallic Superconducting Materials

1) Technical forecast

a) Wires for high critical current densities (above $10^6 A/cm^2$)
b) Wires for superhigh magnetic fields (above 20 Tesla), ac conductors, conductors of large currents (above 10^6 A)
c) Superconducting cable for transmission of alternating currents, coils for large current densities (above $10^6 A/cm^2$)
d) Coils for superhigh microscope (above 20 T), ac coils

2) Basis for assumption

3) Conditions necessary for realization

(3) Oxide Superconducting Materials

1) Technical forecast

a) Fabrication into wires: uniform phase; orientation control; pinning; realization of small-size characteristics; development of large-size conductors; stabilization; compounding; design and development of coils

b) Fabrication into thin films: uniform phase; orientation control; interface control; planarization; tunneling junctions; the technology of lamination; basic technology for fabrication into devices; design and development of devices

2) Basis for calculation

3) Key technical tasks

4) Conditions necessary for realization

(4) Applications in Electronics

Targets: SQUIDs; Josephson device; three-terminal devices; wiring; high-frequency devices; new devices

1) Technical forecast (for both metallic and oxide superconductors)

2) Market scale: the timing of commercialization, and the scale of the market 10 years and 20 years from now

3) Basis for calculation

4) Prospects of technical development

5) Applications for superconductors

6) Specifications of anticipated superconducting systems

7) Key tasks for the future; extraction of social as well as technical tasks and methods for solving them; peripheral technology

8) Conditions necessary for realization: needs; the role of the government; research funds; research structure; research personnel; reliability and safety; international cooperation and competition; comparison with competing technologies; social environment

9) A scenario for realization

10) Impact on society and the economy

(5) Applications in Energy Systems

Targets: Generators; superconducting magnetic energy storage (SMES); accelerators; synchrotron orbit radiation (SOR); magnetic resonance imaging (MRI)

1) Technical forecast (for both metallic and oxide superconductors): practical materials; prototype systems; timing of when an experimental and testing system will be completed; timing of commercialization

2) Market scale: timing of commercialization; the scale of the market 10 and 20 years from now

3) Basis for calculation

4) Prospects of technical development

5) Applications for superconductors

6) Specifications of anticipated superconducting systems

7) Key tasks for the future; extraction of social as well as technical tasks and methods for solving them; peripheral technology

8) Conditions necessary for realization: needs; the role of the government; research funds; research structure; research personnel; reliability and safety; international cooperation and competition; comparison with competing technologies; social environment

9) A scenario for realization

10) Impact on society and the economy

The results of the survey mentioned in (1) are described in 3.1 "Corporate Views of R&D" of Chapter 3, while those of the surveys in (2) through (4) are described in 3.2 Trends of Applications for Patents on Superconductors of Chapter 3.

2.1.3 Results of the Questionnaire

(1) Number of respondents

1) Common questions	17 persons
2) Superconducting materials	6 persons
3) Application in electronics	4~6 persons
4) Applications in energy systems	3~4 persons

2.2 Results of the Survey

2.2.1 Summing Up

In this survey we investigated the growth potential of superconductivity as an industry and some of the important tasks accompanying the growth from the perspectives of both materials and application systems. Superconductivity was investigated from its technical aspects as well as from its market scale. Outlines of the findings are described below.

(1) Superconducting Materials

This section contains forecasts of when the metallic and oxide superconducting materials concerned will attain the technical levels prescribed.

Of the two types of superconductors, metallic superconductors are described in the field of applications in energy systems. As for metallic superconductors, some already have high critical current density capacities above $10^6 A/cm^2$, and lead "chevrel" phase compound $PbMo_6S_3$ and others are being developed as the wire material for superhigh magnetic fields. A majority of opinion says that the technical tasks necessary for superconductor wires will be attained by the year 2000. It is anticipated that superconducting coils incorporating such wires will be realized by the year 2000, or by the year 2010 at the latest (Table 2.2-1).

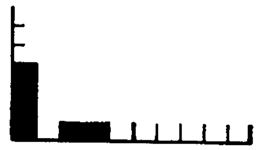
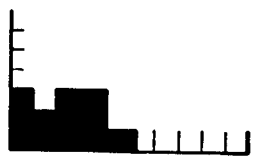
As for fabrication into thin films, it is forecast that the manufacturing technology of thin films itself will be realized by the mid-1990s and that the technologies necessary for fabricating these thin films into devices, such as interconnections, lamination, and microprocessing, will be realized by the year 2000 (Table 2.2-2). It is anticipated that the design and development of such devices will precede the design and development of coils beginning sometime during the years 2000-2010 (Table 2.2-3).

Along with the technical tasks considered important in promoting the technical development of oxide superconducting materials described above are included many problems, and the prospects for their solutions are not so bright. Notwithstanding, the prospects for the realization of oxide superconductors seem as a whole brighter than those for metallic superconductors.

(2) Electronics Field

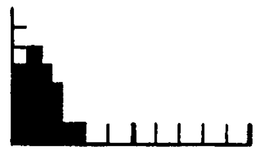
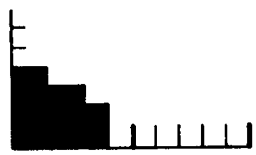
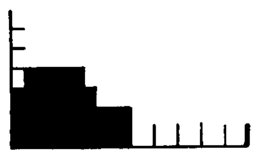
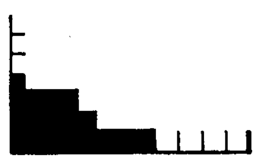
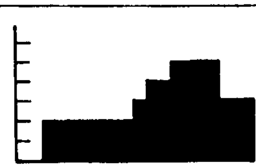
As for the technology for metallic superconducting materials, superconductors have already been incorporated in Josephson devices, SQUIDs, and high-frequency devices and interconnections, and these devices are at the stage of trial manufacture and evaluation of prototypes. As for SQUIDs, in particular, simple superconducting products have already been commercially developed and placed on the market. The three-terminal devices and new devices, on the other hand, are positioned as new technologies requiring much exploration and the forecast is that it will be a long time before they hit the market as commercial products.

Table 2.2-1. Forecasting the Period for Commercialization of Superconductors (Metallic Systems)

Technical item	Estimated period 1990 2000 2010	Comments
High critical current density wire (10^6 A/cm^2 up)		Materials having critical current density Jc above 10^5 A/cm^2 have already been developed. For stability and for protection from quenching, wires made of these materials are used at the levels of $10^4 \sim 10^5$ A/cm^2.
Superhigh magnetic field wire (above 20 T)		Metallic wires of Nb_3Al, $Nb_3(Al, Ge)$, and $PbMo_6S_8$ are being developed for use in magnetic fields above 20 T. A major technical task is their fabrication into long-size wires or coils.
AC conductors (50 ~ 60Hz)		Advances in fabricating fine filaments have attained low losses at the levels of wires. Development is under way to attain low losses at the levels of conductors.
Large-current conductors (above 10^6 A)		These conductors are expected to find uses in large-size equipment such as SMES. The period of their commercialization will be determined by the demand for them. Development of equipment to twist wires into a cable and development of protective measures in case of an abnormality are awaited.
Superconducting AC transmission cable		Superconducting power transmission is hardly to be realized by liquid helium refrigeration, but if such systems prove to be advantageous, the pace of their development may accelerate.
High current density coils (Above 10^5 A/cm^2)		Depending on magnetic fields, such coils are available even now, but only coils having small storage energy levels are feasible in order to protect them from quenching.
Superhigh magnetic field coils (Above 20 T)		These coils are expected to find applications in high-resolution NMR machines or in solid-state research, so they have a good chance of being commercialized in a few years after superhigh magnetic field wire has been put to practical use.
AC coils (50 ~ 60Hz)		These coils are expected to find applications in electric power systems such as generators and transformers. The period of when such coils will be realized depends on when the AC conductor will be developed and what advantages systems incorporating such coils will have.

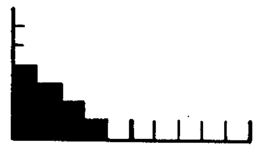
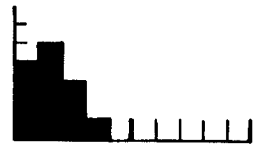
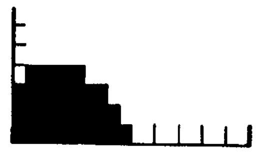
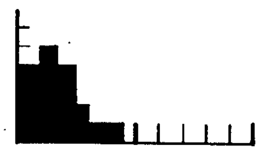
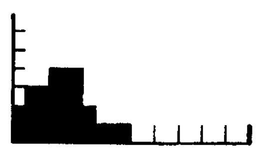
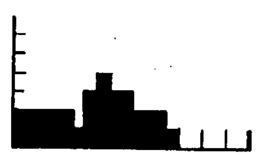
Note: Axis of ordinate: Number of respondents in the questionnaire survey.
Axis of abscissa: Estimate on the period of realization.

Table 2.2-2. Forecasting the Period for Commercialization of Superconductors (Oxide Systems)—Fabrication Into Wire

Technical item	Estimated period 1990 2000 2010	Comments
Homogeneous phase		• In the Y family of superconductors, the goal is near realization. • In the Bi-based superconductors, X-ray analyses have proved the phase to be homogeneous but superconductivity has yet to be obtained throughout the phase.
Orientation control		• In the Y family, an orientation in the direction of the c axis has been obtained by the melt growth method, sheath rolling method, or pressing method. No orientation is obtained in the directions of the a-b axes.
Grain boundary control		• Grain boundaries having a large angle of inclination have been reduced by the melt growth method. • It has been reported that in the Bi family, a combined use of rolling and pressing of the silver sheath material enables the consistency of the grain boundaries to be improved, but no details are available.
Introduction of pinning		• Following are the four kinds of pinning centers: (1) Intrinsic matching surface on Cu-P plane (2) Precipitation phase observed in the 211 phase of the Y family (3) Twin crystal surfaces (4) Exposure defects
Realization of short-size characteristics		• In both the Y and Bi families, the current density of $10^4 A/cm^2$ has been obtained at 77 K in nonmagnetic fields by the silver sheath rolling method.
Development of long-size conductors		• In the case of silver sheath conductors, fairly long-size products have been developed, but they have problems with electrical and mechanical homogeneity.
Stability		• Too many flux jumps occur in high magnetic fields. Flux creeps are also large. • Fabrication into strands of multicore fine wires may be needed.
Compounding		• Only Ag and its alloys are currently being tried as the sheath material. • None of the materials has yet been found to contribute to an increased structural strength.
Design and development of coils		• A spectrum of the properties found in the existing wires and cable is demanded. • At present, the prospects are bleak except for the laboratory-level solenoid coils.

Notes: Axis of ordinate: Number of respondents in the questionnaire survey.
Axis of abscissa: Estimate on the period of realization.

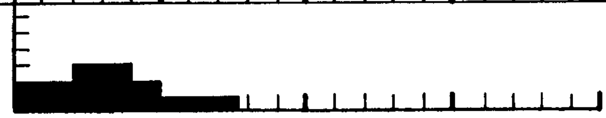
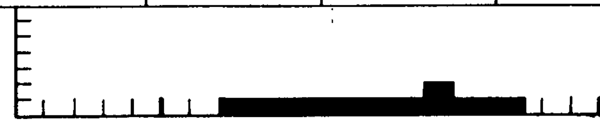
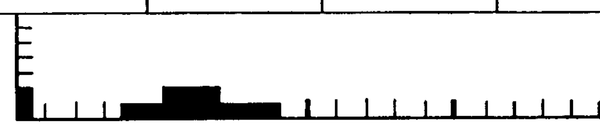
Table 2.2-3. Forecasting the Period for Commercialization of Superconductors (Oxide Systems)—Thin Films

Technical item	Estimated period 1990 2000 2010	Comments
Homogeneous phase		• The goal is near realization through technology that is an extension of existing thin film technology. • The know-how on the equipment proper exists.
Orientation control		• In the Y family, c axial orientation has already been obtained, but c planar orientation has yet to be obtained.
Interface control		• Control of the interface is affected by the existence or nonexistence of a reaction between the conductor and substrate. Consequently, development of technologies for growing films at low temperature and for fabricating buffer layers is needed.
Planarization		• It has been reported that smoothness at the level of atoms has been obtained through existing technologies, such as sputtering.
Tunneling junctions		• The basic J-J characteristics have been obtained, but their reproducibility is low. • Microprocessing technology at the order of the coherence length is needed.
Lamination technology		• The technology for inhibiting mutual diffusion at the interface between layers and heteroepitaxial technology must be developed.
Microprocessing technology		• A processing scale at the level of the coherence length is needed. • The superconducting properties must be kept intact after processing.
Basic technology for device fabrication		• SQUIDs have been test-manufactured, but the technology is low in reproducibility. • $10^8 A/cm^2$ is needed for wiring.
Design and development of devices		• Device technology is considered at the level of an extension of LSI technology. • Control of the properties, including heat and noise, is needed at an atomic layer level.

Notes: Axis of ordinate: Number of respondents in the questionnaire survey.
Axis of abscissa: Estimate on the period of realization.

Table 2.2-4. Period for Commercialization of Application Systems and Their Market Scale (Electronics) (1) Metallic Systems

(Unit: ¥100 million)

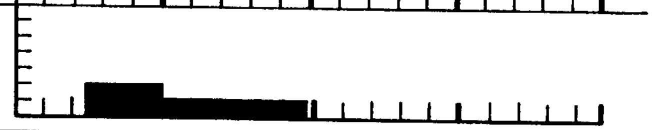
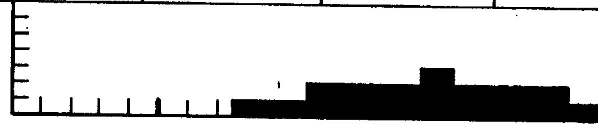
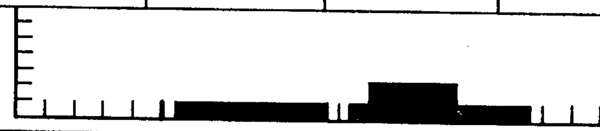
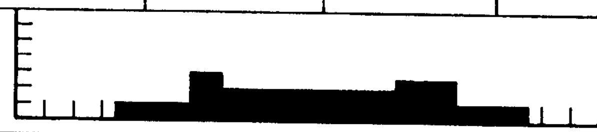
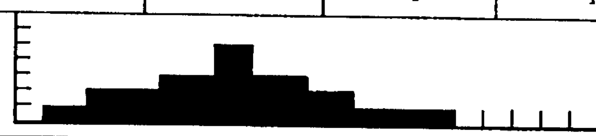
Application system	Item	Calendar year 1990 2000 2010 2020 2030			
SQUID	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		1990–2000 1995–2010	10 0.1	100 1	1,000 250
Josephson devices	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		1996–2020	100	1,000	10,000
Three-terminal devices	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2010–2030 2010–2020	350 100	10,000 1,000	15,000 10,000
Wiring	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2010–2020 1997–2002	100 1	100 10	10,000 10
High-frequency devices	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2000–2008 1997–2003	10 1	20 2	30 3
New devices	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2003–2012	100	200	300

(1) Period of commercialization Axis of ordinate: Number of respondents.
Axis of abscissa: Period of commercialization.

(2) Market scale Top tier: Largest estimate (from the results of the survey).
Bottom tier: Smallest estimate (from the results of the survey).

Table 2.2-5. The Period for Commercialization of Application Systems and Their Market Scale (Electronics) (2) Oxide Systems

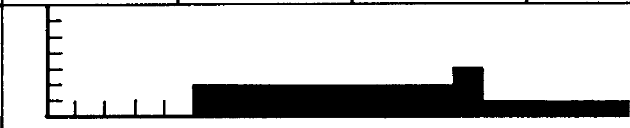
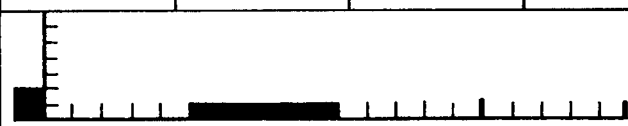
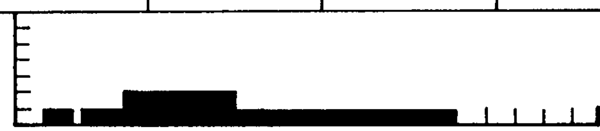
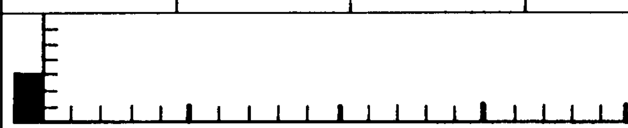
(Unit: ¥100 million)

Application system	Item	Calendar year 1990 2000 2010 2020 2030			
SQUID	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2000 – 2010 1995 – 2000	1 0.002	50 0.5	500 10
Josephson devices	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2005 – 2030	100	1,000	10,000
Three-terminal devices	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2002 – 2012	350	15,000	30,000
Wiring	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2005 – 2015 1997 – 2004	100 0.1	100 1	10,000 1
High-frequency devices	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2000 – 2020 2004 – 2013	1 2	500 4	– 8
New devices	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2010 – 2030 2015 – 2020	500 100	1,000 1,000	2,000 –

(1) Period of commercialization Axis of ordinate: Number of respondents:
Axis of abscissa: Period of commercialization.
(2) Market scale Top tier: Largest estimate (from the results of the survey).
Bottom tier: Smallest estimate (from the results of the survey).

Table 2.2-6. The Period for Commercialization of Application Systems and Their market Scale (Energy Systems) (1) Metallic Systems

(Unit: ¥100 million)

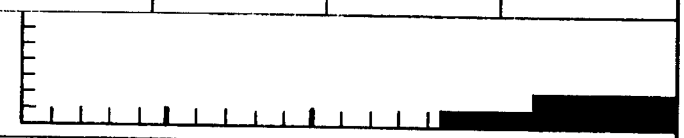
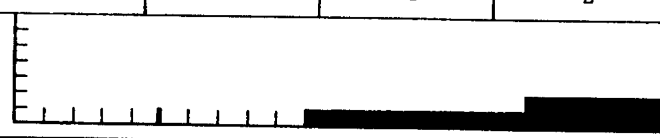
Application system	Item	Calendar year 1990 2000 2010 2020 2030			
Generator	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2010	100	900	2,000
S M E S	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2010 – 2020	50	100	200
Accelerator	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2000 – 2010 Commercialized	200 5	20 10	— 20
S O R	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2010 – 2020 1998 – 2010	50 2	250 2	2,500 2
M R I	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		Commercialized Commercialized	700 1	2,250 50	2,750 50

(1) Period of commercialization Axis of ordinate: Number of respondents.
Axis of abscissa: Period of commercialization.

(2) Market scale Top tier: Largest estimate
Bottom tier: Smallest estimate

Table 2.2-7. The Period for Commercialization of Application Systems and Their Market Scale (Energy Systems) (2) Oxide Systems

(Unit: ¥100 million)

Application system	Item	Calendar year 1990 2000 2010 2020 2030			
Generator	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
S M E S	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
Accelerator	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2025 – 2025 –	20 20	40 —	40 –
S O R	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2030 – 2020 – 2030	40 2	200 2	2,000 2
M R I	Period when the device will be commercialized				
	Scale of the market for the device	Device will be commercialized	Initial cost	After 10 years	After 20 years
		2020 – 2010 – 2030	20 50	550 50	— 50

(1) Period of commercialization Axis of ordinate: Number of respondents.
Axis of abscissa: Period of commercialization.

(2) Market scale Top tier: Largest estimate
Bottom tier: Smallest estimate

The data on when electronics using metallic superconductors will be commercialized and what their market scale will be are given in Table 2.2-4. The horizontal column for market scale is divided into two tiers; the largest forecast (as gained in the questionnaire) is given in the top tier and the smallest forecast in the bottom tier. Of the various applications of superconductors, their uses in high frequency devices require liquid helium as a refrigerant, with the result that these products will find use only in special fields. Consequently, the market for superconducting high-frequency devices will not grow to any great extent. SQUIDs and Josephson junctions (used in computer), on the other hand, are forecast to grow into a ¥10~100 billion per year market and a ¥1 trillion per year market, respectively. The market for three-terminal devices, used in superconductors after Josephson junctions, is forecast to grow to ¥1 trillion to ¥1.5 trillion per year. Opinions are widely divergent on the merits of superconducting interconnects, and consequently the market forecasts are also widely divergent.

In oxide superconducting materials, their reliability and stability as material have not yet been proven, and furthermore they harbor many technical problems such as junction, lamination, etc. For these reasons, the forecast is that it will be a long time before they are produced commercially.

The data on when devices incorporating oxide superconductors will be commercialized and what their market scale will be are given in Table 2.2-5. Once systems incorporating oxide superconductors have been commercially developed, the markets for three-terminal devices and new devices will be larger than those for their metallic counterparts. Pending the development of a simple refrigerating device, high-frequency devices will find uses in home electronics, such as the cellular telephone, and the market is expected to grow substantially. As is the case with interconnects based on metallic superconductors, the forecasts for the market scale for interconnects based on oxide superconductors are widely divergent. The market for oxide SQUIDs is forecast to be smaller than the market for their metallic counterparts, and this is believed to be caused by the anxieties of those polled: Is it really possible to develop commercial oxide SQUIDs? Wouldn't such products be usable only in applications of lower performance compared with magnetoencephalography?

With the exception of the microscopes that are nearing the stage of perfection, as stated above the technologies for fabricating oxide superconductors into devices have scarcely been established, and furthermore the superconductors themselves have far to go in terms of reliability and stability. Another big problem is that depending on the field of application, some superconductors require much higher critical temperatures than those needed for Ti systems, and long, arduous research will be needed.

(3) Energy Field

The technology for superconducting SORs based on metallic superconductors has not yet been fully established, but superconducting large-scale accelerators and MRI machines have already been produced commercially. As for superconducting power generators, a prototypical partially superconducting electric generator is being developed by the Superconducting Power Generation Equipment

and Materials Technology Research Association (Super-GM). Small- and medium-scale SMES prototypes have already been completed, and development of a practical-scale permanent current switch is awaited. As shown in Table 2.2-6, commercial production of generators (low- and superhigh-speed machines), SMES, and SOR machines is expected to start around 2010, 2000~2020, and the first half of the 2000s, respectively. The expression, "commercialization of accelerators in the year 2000 or so," is used to mean that in some special fields superconducting accelerators, such as the superconducting super collider (SSC) of the United States and the large hadron collider (LHC) of Europe, will be realized.

The market for generators is expected to reach a scale of ¥200 billion per year at best, and the forecasts for SOR and MRI machines are all optimistic. The forecast for SMES is ¥20 billion per year.

The technology of fabricating oxide superconductors into wire has yet to be established, so their commercialization will take much longer than is needed for metallic superconductors. As shown in Table 2.2-7, the debut of commercial superconducting accelerators, MRI machines, and SORs based on oxide superconductors is forecast for the 2010~2025 period or later, and commercial superconducting generators and SMES are forecast to hit the market after the year 2030.

If oxide superconductors are to find uses in the fields mentioned above, the development of the technology that will enable oxide superconductors to be fabricated into wire as readily as metallic superconductors is absolutely needed. The road to that goal is filled with many technical problems, such as improvement in the critical current density, longer wires, multicore cable, stability, compounding, development of large current capacity conductors, and joints. Consequently, the research on the application of oxide superconductors in the energy field is anticipated to take as much or more time as that needed for the research on their application in the electronics field.

(4) Social Needs

If superconducting systems are to be commercialized, social needs must exist for them. In the case of the needs for superconducting electronics, SQUIDs, and high-frequency devices have no competitors that can surpass them in terms of their sensitivity to magnetic fields and frequency bandwidth. The needs for Josephson devices are expected to arise when the semiconductor supercomputer has hit the technical wall and the industry has started to look for some alternative that supersedes semiconductors. As for high-frequency devices, although they have no competitor, they are considered to have little application in commercial products; hence, the market for them is forecast to be very small.

In the energy field, superconducting systems are anticipated to find full social needs thanks to their low-loss features. In other words, an increasing demand for electric power and the requirements for high efficiency will demand the realization of superconducting electric generators, and SMES will also be needed for a stable supply of electric power. SORs will find industrial use as

the tools for precision processing of semiconductors as well as medical apparatuses in the treatment of cancer, while MRI machines will be used for medical purposes. These have no competitors and hence there are social needs for them.

One competitor of the application of oxide superconductors is the family of metallic superconductors. Oxide superconductors have an advantage over metallic superconductors in that they operate at the liquid nitrogen temperature, thereby contributing to the ease of systems refrigeration. However, in SMES and MRI machines the difference in the cooling media, that is, liquid helium vs. liquid nitrogen, is not calculated to have as decisive an advantage as is supposed. In such cases, oxide superconductors will have to possess some advantages over metallic superconductors in other aspects, such as the ease of manufacture and the ease of handling, for example. On the other hand, since oxide superconductors can operate at the liquid nitrogen temperature, small-size devices may find uses in consumer appliances or their equivalents, provided simple cooling equipment has been developed. One such application is the use of oxide superconductors in mobile communications, and SQUIDs may also find a widespread use after simple cooling equipment is developed. Then, the market for oxide superconductors will expand.

(5) Requests To Make of the Government

As for the research on applications of superconductors, work is under way to develop prototypes of large superconducting systems based on metallic superconductors in the fields of electronics and energy systems. In the field of oxide superconductors, on the other hand, the fundamental technologies needed to fabricate them into devices or to draw them into wire have scarcely been established.

As is forecast in this report, the research on applications of oxide superconductors will extend over a long period. The result is that the investment risks for the research are high, so it is expected the government will come up with a broad scheme to help the R&D activity financially. Since the fundamental technologies for oxide superconductors have scarcely been established, it is considered difficult to predict the future development. Some say that the government should provide assistance for technical difficulties that may occur. One way of seeing it is that private businesses on their own initiative will research whatever technologies are considered technically feasible.

As for metallic superconductors, it is important to continue the ongoing research activity to develop large-scale superconducting commercial systems. The concerted research efforts for oxide superconductors must not be done at the expense of research on metallic superconductors, because the application technology of superconductors is anticipated to center on metallic superconductors in the immediate future. Consequently, it is desired that the government help large-scale projects involving metallic superconductors with increased research funds and that it will lead the effort to set up a cooperative research structure.

2.2.2 Superconducting Materials

(1) Metal-Based Superconducting Materials

A questionnaire survey was conducted of the technical development of metallic superconductors. There were six respondents. The results of the survey on technical forecasts are given in Table 2.2-1, and the results of the survey on a scenario for the development of metallic superconducting materials are given in Figure 2.2-1.

1) Technical Forecasts

A survey was conducted to find out what technical tasks are needed to further expand use of superconducting wire, conductors, and coils in power systems. The items for survey were the high critical current density ($J_c \geq 10^6 A/cm^2$) wire material; the superhigh magnetic fields (applied magnetic field ≥20 T) wire material; ac conductors for commercial frequencies; and large-current conductors (current capacity $\geq 10^6 A$) in the category of wires and conductors; as well as the superconducting ac transmission cable; high current density coils ($J_c \geq 10^6 A/cm^2$); superhigh magnetic field coils (generated magnetic field ≥20 T); and ac coils for commercial frequencies, for a total of eight. As for the fields of applications of these superconducting materials, the large-current conductors are expected to find uses in large-scale equipment such as SMES and nuclear fusion equipment, the high-current density coils in SORs and accelerators, the superhigh magnetic coils in solid-state research equipment, and the ac coils in superconducting electric generators and superconducting transformers.

As for high critical current density wires, the opinions of the respondents are relatively close in that they say that such wires have already been developed or that they will soon be realized. As for the critical current density per superconductor, in low magnetic fields a high critical current density of $10^6 A/cm^2$ has been realized in such materials as NbTi and Nb_2Sn, but the actual current densities available for wires are at the level of $\sim 10^5 A/cm^2$ since these materials are compounded with stabilizing materials such as Cu and Al when they are drawn into wire to maintain the stability of the produced wires as well as to protect them from quenching. Pending improvements on the processing process, introduction of artificial pinning, which will raise the critical current density, and studies on the stabilizing method, wires for practical use may be developed from these materials. For increased critical current densities, theoretical and experimental R&D efforts must be exerted continuously.

Wires based on Nb_3Al, $Nb_3(Al, Ge)$, or $PbMo_6S_8$ are being developed for use in superhigh magnetic fields. In the $PbMo_6S_8$ wire, critical current densities above $10^4 A/cm^2$ have been achieved. In view of this development, the majority opinion is that the use of the wire in superhigh magnetic fields will be commercialized in two to six years. The future tasks are the manufacture of a long-size wire and its demonstration use in the manufacture of coils.

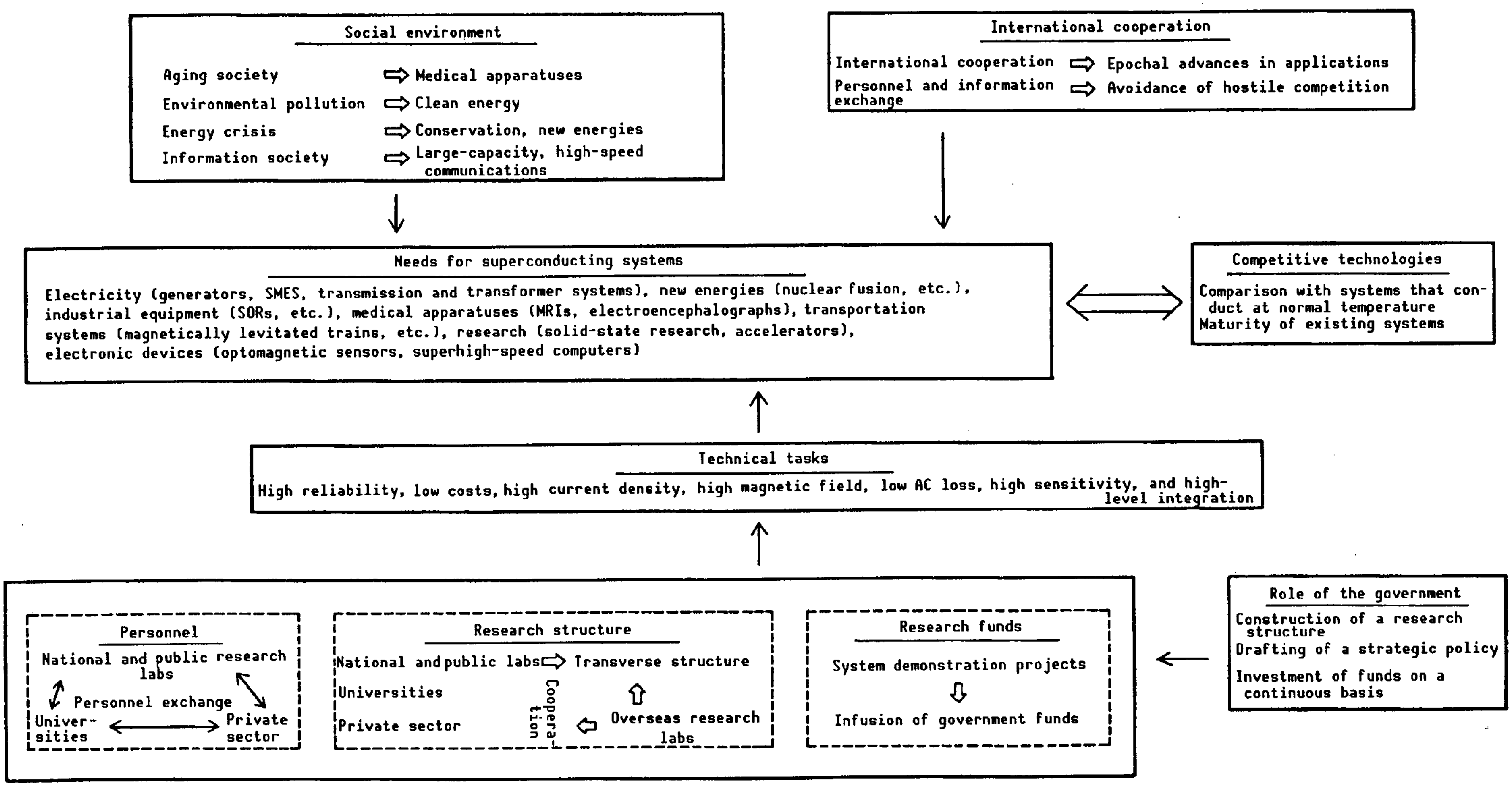


Figure 2.2-1. Scenario for Development of Metallic Superconducting Materials

The forecast for an ac conductor is that it will be developed within eight years. Thanks to advances in the technology for making small-size filaments, low losses have been achieved at the level of raw wires, and research is being promoted to realize low loss in conductors.

As for large-current conductors, opinions are divided. Conductors above the 10^4A class are already used in nuclear fusion equipment. As to when large-current conductors will be commercialized, that will probably be determined by what strong requirements exist for them from the equipment side, but technically development of the wire twisting and processing equipment and development of protective measures in case of abnormalities are needed.

Opinions are completely divided on when superconducting cable for transmission of alternating current will be commercialized. The majority opinion is that commercialization of such a cable will be far in the future as long as it is refrigerated by liquid helium.

To the question of when the high current density coil, superhigh magnetic field coil, and ac coil will be commercialized, the respondents gave different estimates. High current density coils are now used at the average current densities of coil below $5 \times 10^4 A/cm^2$. In the case of high magnetic field coils, 20 T has been realized by using superfluid helium as the coolant (1.8 K), but the task now is refrigeration at 4.2 K, a temperature superior in terms of operability and reliability. For any of the three types of coils to be realized, technical developments in the fields of stability, protection against quenching, and measures to cope with electromagnetic forces are needed. In the case of the ac coil, in particular, whether or not it will be realized is also affected by what advantages it will display when incorporated in ac systems such as electric power systems.

Research has long been conducted on metallic superconductors, and there are many cases in which metallic superconductors have been used in equipment and systems. Spurred on by the discoveries of oxide-based superconducting materials, the R&D of metallic superconductors is expected to progress quickly.

2) Scenarios for Development

Based on the opinions obtained in the questionnaire survey, the scenarios necessary for promoting metallic superconductors are described below (Figure 2.2-1).

Reflecting social changes such as the increasing age of the population, environmental pollution, the energy crisis, and an advanced information society, a strong demand for superconducting systems exists in such broad areas as electric power, energy, various industrial and medical apparatuses, transportation systems, and electronic devices. Superconducting technology is considered especially suited to meet the demands of the age, such as conservation and compact product size, and superconducting technology will be able to display its full potential in such fields as nuclear fusion, MRI machines, and SQUIDs. On the other hand, in those areas where the existing competitive systems such as electric power, industrial equipment, and

communications devices are reaching the stage of maturity, superconducting technology is hard pressed to show superiority over existing technologies. However, in some areas, such as electric power systems, the adoption of superconducting systems is considered to bring about a qualitative innovation, and hence it will be especially necessary to demonstrate the superiority of superconducting systems. To do so, because there are so many "if's" with oxide superconductors, the focus is naturally directed toward metallic superconductors, of which practical wires have already been developed. Great expectation is placed on metallic superconductors.

To meet such strong needs, the goals for superconducting wires and coils are to realize high current densities, high magnetic fields, and low ac losses, while those for superconducting electronic devices are to realize high sensitivities and high-level integration. To solve such technical tasks, it will be necessary to establish a collaborative research structure by tapping the resources of academia, government, and industry and seeking active government assistance. To promote R&D by the private sector, it is desired for the government to come up with a strategic policy to break down the barriers to private efforts for replacing the existing technologies with superconducting technology. Large-scale projects such as the construction of pilot plants for demonstrating the applicability of superconductivity to superconducting systems have great risks, so the support of the government from the drafting stage of a project to the provision of necessary funds to the establishment of a cooperative research structure is indispensable. As the current systems research is centered on metallic materials, consideration is needed so that financial support in research will not be directed solely toward oxide materials.

It is desired to promote personnel exchange between the national and public research laboratories, universities, and private industries, and at the same time to establish a transverse structure of these organizations to promote research efficiently. Active personnel exchange will not only promote an exchange of various ideas from diverse research fields but also may help open up a new horizon. Among the research methods are a dispersed type of research in which the participants in a research association take their research themes back to where they come from—national labs, universities, or private industries—to conduct research and a concentrated type of research in which the organizations participating in joint research dispatch their researchers to the research site. An example of the former type of research is the "Superconducting Power Generation Machinery and Materials Technology Research Association," which is engaged in developing wire and cable materials for electric generators. An example of the latter type of research is the ISTEC (International Superconducting Industrial Technology Research Center), which is engaged in research on a broad range of oxide superconducting materials. Both types of research are achieving excellent results. As for metallic superconductors, a majority opinion is that a dispersed type of research is desirable since the research setup will make it possible to take advantage of the research structure, personnel, and experience that each of the participating organizations has been fostering up to now. Many years of research on metallic superconductors have enabled them to win a high level of trust for reliability, but to further advance their reliability it is desired that the

national and public research laboratories institute evaluation standards in keeping with technology advances and their timely renewals.

Promoting international cooperation is also indispensable for the increased growth of superconducting technology. The maintenance of an international cooperative relationship based on respect for individual countries' independence has great meaning in that such a relationship would prevent the countries concerned from engaging in hostile competition. Japan especially is being sought to positively show its research achievements to the world to contribute to the growth of the technology. In the superconducting field, academic meetings and symposia in Japan have been held under an open-door policy, and Japan has also participated in the international cooperative project on materials evaluation Versailles Project on Advanced Materials Standard (VAMAS). In this respect, Japan is well prepared to cooperate. To ensure continued growth of cooperation, the government is requested to support such efforts to international cooperation with some policy measures.

The discoveries of high-temperature superconductors have increased the understanding of society of superconductivity and have laid a favorable ground for the promotion of research and development, all of which increase the changes for superconductors to enter into social systems. For this to occur it will be necessary to consider needs not only from the perspective of advances of materials but also from a macroscopic viewpoint of what applications these superconductors will have in systems.

(2) Oxide-Based Superconducting Materials

1) Technical Forecast

Answers were obtained from five persons on the technical forecast for oxide superconductors. Table 2.2-2 gives the years forecast by the respondents for the commercialization of superconducting wires, and similarly Table 2.2-3 gives the years forecast for the commercialization of superconducting thin films.

a) Wire

It is forecast that the fundamental properties of wire, such as homogeneous phase, suppression of fluctuations in structure, orientation control, and introduction of pinning, will be commercialized by the year 2000 or so. As for applications, short-size characteristics are forecast for commercialization by the year 2000 or so, and the technology of fabricating long-size wires is forecast for commercialization as soon as pinning centers are introduced. It is forecast that the whole wire-fabrication technology, including stabilization and compounding, will be accomplished by the year 2005. The design and development of coils will be accomplished by the year 2010 or so. That is, by the early 21st century the technology for fabricating superconducting materials into wire and coils will have been developed.

b) Thin films

It is forecast that the fundamental properties of thin films, such as homogeneous phase, orientation control, interface control, and planarization, will be commercialized by the year 1995 or so. It is considered that the development of the technologies for these fundamental properties will coincide with the development of the technology for drawing superconducting materials into wires. As for applications of thin films, the tunneling junction technology, lamination technology, microprocessing technology, and basic technology for devices are all expected to be developed by the year 2000 or so. However, the design and development of devices using oxide superconductors will be accomplished during the 2000-2010 period.

c) Grounds for technical forecasts

If we assume that overall materials development is to be computed based on the growth of discrete fundamental technologies, we have to first forecast the period when each of the fundamental technologies will be accomplished. How to establish the basis for the forecast is a highly important issue. One method is to use similar instances in the past as the models. This method of forecasting leads one to a mistaken judgment because it is based on the logic that the development of the peripheral technologies progresses in parallel with the development of some targeted material. However, during the time when people are focusing their efforts on the development of some material, it is often beyond their capability to know what peripheral technologies are developing at what speed or how those technologies will contribute to the cause of the material's development. This is the reason why it is difficult to forecast the changes in the technical environment surrounding materials. Consequently, when forecasting when some technology will be developed, one must make the estimate after considering the development of peripheral technology, including probable changes in the technical environment.

A second method is to rely on social and technical experience, including one's own. A majority of the results obtained in the current questionnaire survey seem to have been based on intuitions coming from experience. As with human society, in science and technology development the principal players are humans, so arriving at a perfect forecast is hardly to be expected. In predicting the development of oxide superconductors, an assumption is that the enterprises currently engaged in the R&D of superconductors will not scale down their research efforts. A reduced researcher population would lead to a diminished percentage of breakthroughs. So, predicting whether the current researcher population will be there several years from now that is, an estimate on the manpower engaged in R&D is an important factor when considering technical development.

Drawing lessons from past developments of existing materials, the respondents gave the time frames of 5 to 10 years and 10 to 15 years. Technically, some aspects of the development are shrouded in complete darkness, and hence the above forecasts are not necessarily based on any firm information. How the respondents evaluated the progress of technical development in the three-year period following the discovery of the oxide superconductor is reflected in their forecasts on when the particular technology will be developed.

2) Future Priority Tasks

a) Drawing into wire

The key words that have emerged from the survey results are the following four: 1) homogeneous phase and introduction of pinning centers; 2) increased critical current density in magnetic fields; 3) long-size wire through the control of grain boundaries, stabilization, and compounding; and 4) flexible properties. These technical tasks can be summed up as follows: From the perspective of properties, the task is to increase the critical current density, while from the viewpoint of the ease of use, it is to raise the mechanical properties. Each task is very tough.

Regarding the aspect of properties, in raising the critical current density the first tasks are obtaining homogeneous phase and controlling grain boundaries. In oxide superconducting materials the junctions of grain boundaries and their structures are considered to be the main culprits contributing to the deterioration of the critical current density inside the grains and on single crystals. The problem is that the crystalline grains do not contact each other across their entire surfaces but do contact partially. This is to say that the absolute value of the intergranular area that conducts currents is small. The points where grain boundaries come into contact are considered to be the bottleneck, and their total area is considered to be a fraction of the total of grain surfaces. Consequently, compaction of the grain boundaries is highly important. The manufacturing process of the raw materials for oxide superconductors is not so different from that of ceramics. Therefore, various phenomena that show up in the manufacture of ceramics are also the prevailing phenomena in the manufacture of the raw materials for oxide superconductors. That is, the structures of the raw materials are determined by such phenomena as compaction, grain growth, and uniform or random orientation during their sintering.

Introducing pinning centers is most important. Among the major candidates considered as the potential sites for introducing pinning centers in oxide superconductors are the insulating layers between Cu-O planes, fine precipitations, twin surfaces, and exposure defects. No decisive conclusion has been obtained for any of these techniques but discussions will have to be based on solid experiment results in the future.

The respondents have not given much attention to the problem of orientation. Obtaining an orientation in wire at the level of basic research in labs, which will improve the champion characteristics in some direction, is viewed with doubt as to how large an advantage it would bring forth. Wire is used in electromagnetic applications. Therefore, when the rotation of magnetic flux, for example, is considered, having no orientation is more advantageous. Deterioration in the critical current density must be avoided by all means from whatever direction strong magnetic fields may be applied.

From the perspective of ease of use, some respondents pointed out that wires need to be flexible. In their applications as transmission cables or coils, wires are required to be high in tensile strength, yet be flexible.

Prior to that, from the perspective of transportation of wires or storage space for them, it is very convenient if such wires can be coiled.

From the perspective of wire applications, stability and compounding of wire are highly important. Depending on the mode or kind of pinning center introduced, however, these techniques may not be available. Elucidating and introducing the pinning center is the task with the highest priority. Furthermore, if wires are incorporated into systems and strong currents flow into them, the electromagnetic stresses generated may be too strong, so their mechanical strength characteristics are also an important factor. Consequently, the approaches to stability and compounding of wire must be considered after taking into account the requirements for wire structure.

If ceramic wire is to be manufactured by using the same technology used to manufacture metallic wire, the next question is, what metals will be most suitable to use as the sheathing material for ceramic wires. The kind of metals that reduce oxides in the superconductors, i.e., those metals that are easily oxidized at the range of the sintering temperatures of these superconductors, will not stand use. Consequently, the candidates are superalloys, or precious metals or their alloys. The sheathing material is required to supply oxygen to the superconducting material during the course of its sintering. Efforts will naturally have to be made to develop sheathing materials.

b) Thin films

Development of good-quality thin films is progressing smoothly, and now device concepts are needed. Aiming at development of concrete devices, the technologies for lamination, microprocessing, and proper interface are developed according to the needs. Because of the advances in the technology for making thin films out of semiconductors, as is evidenced in super-large-scale integrated manufacturing, electronics readily come to mind when thin films are mentioned. However, thin films of oxide superconductors do not have to be limited to their application in electronics. It is about time to start thinking about applications in other fields. If the technology has advanced to the level where thin films of superconductors display superconductivity without the final heat treatment or with a heat treatment at temperatures that are just enough to clear the heat resistance capability demanded of the device incorporating them, such thin films will find use in a wide range of applications.

3) Conditions Needed for Realization

a) About needs

In that oxide superconductors need refrigeration, they are no different than conventional metallic superconductors. Since utilities of existing metallic superconductors are well established, it is hard to say if the advantage of oxide superconductors—the availability of refrigeration at liquid nitrogen temperature—is strong enough to induce the user to switch over to them.

When oxide superconductors have been commercialized, if they are to find use, they must have an advantage over metallic superconductors in one of the following areas—high performance characteristics, ease of use, low cost, and properties. Furthermore, rather than placing too great a hope on their advantage of refrigeration using liquid nitrogen, we should strive to develop applications that oxide superconductors alone can do.

b) Role of government

Many respondents call for the government to extend financial help when starting projects or undertaking international cooperative projects. As for oxide superconductors, little has been known of their fundamental technologies, so technically speaking, much of the development outcome is unpredictable. Some say that government assistance is needed to develop technologies whose feasibilities are unforeseen. As for the technologies whose applications can be foreseen, the enterprises, it is anticipated, will undertake research on their own.

c) Research funds

A majority opinion says that the government should spend several billion yen over 10–20 years.

d) Research structure

Some say that a concentrated research structure such as the one adopted in ISTEC will be effective. In those R&D tasks whose solutions are forecast to take a long time, the most effective research structure would be for the private enterprises to invest to the tune of several hundred million yen and to dispatch researchers.

e) Personnel

A majority opinion says that talented people, including foreign researchers as well as Japanese researchers from academia, industry, and government, should be recruited from a broad range of disciplines.

f) Reliability and safety

The establishment of a checklist to evaluate a material and of standards that material must satisfy is an indispensable precondition. Developing a material having some needed properties does not directly lead to its use in some devices. Even if some material has been proven to possess excellent basic properties, it usually takes a long time before the material is judged capable of displaying its properties in industrially mass-produced products or before the material is proven to meet the use standards. The result is that a long delay exists between the development of a material and the start of its commercial production. Also, the material will have to be evaluated as to its reliability in repeated practical tests or field tests.

g) International cooperation and competition

All the respondents agree on the need to promote international cooperation.

h) Comparison with competing technologies

Oxide superconductors and metallic superconductors are competitive in terms of electromagnetic properties, mechanical properties such as ease of use, and costs. Oxide superconductors also compete with semiconductor devices in terms of electromagnetic properties, noise characteristics, and costs. However, oxide superconductors are not yet in competition for practical applications.

i) Social environment

While social environment helps facilitate the growth of technology, technological progress in turn alters the social environment. If the research on oxide superconductors and the development of superconducting materials are to lead the growth in the peripheral technologies, the ripple effects they will have on other technical fields will be enormous. As the recent interest of the general public in high technology has been heightened by oxide superconductors, oxide superconductors have been highly effective in expanding the technical base. This in turn will strengthen the social foundation where people accept new technologies.

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2.2.3 Electronics Field

(1) SQUIDs

Four answers were obtained on SQUIDs. Table 2.2-8 gives technical forecasts and market scales. Explanations are given separately on metallic SQUIDs and oxide SQUIDs.

1) Technical Forecasts and Market Scales

a) Metallic SQUIDs

• Technical forecast

Nb-based SQUIDs are already in the stage of technical maturity, and they have been used in such commercial products as measuring instruments of magnetic susceptibility, measuring systems of magnetic fields in vivo, and precision measuring instruments. Development of a large medical system incorporating SQUIDs is under way. As for the use of SQUIDs in medical apparatuses, such systems will have to undergo many clinical trials before they are commercialized, but the tests will be completed by the year 2000 at the latest.

• Market scale

The scale of the market for SQUIDs varies greatly depending on how they are counted. That is, one method is to calculate the value of SQUIDs themselves and another is to calculate the value of systems using SQUIDs. When SQUIDs are manufactured in large quantities, as is the case with semiconductors, their costs are expected to drop to ¥1 million including the price of the drive circuitry. Once the costs are lowered, SQUIDs are expected to find an expanding market from such applications as nondestructive testing and leakage magnetic field testing. When medical systems incorporating SQUIDs are counted, the potential market is expected to be fairly large.

• Prospects for technical development

Basic properties of SQUIDs have already been evaluated. Improvements in the Josephson junction-forming technology, microprocessing technology, and lamination technology will lead to the development of higher-performance SQUIDs. Combining use of SQUIDs with a refrigerator will expand the scope of their applications.

• Schematic specifications

SQUIDs are expected to find use as sensors, logics, and memory devices. For medical applications, SQUIDs are required to have a sensitivity level that enables them to diagnose the magnetic fields in the brain, which is $10^{-6}\ \phi_0/\sqrt{Hz}$. When used as a measuring system of magnetic fields in the brain, the SQUID will have dimensions of about 3 m x 3 m x 2.5 m, including the size of the magnetic shield room.

Table 2.2-8. Technical Forecasts and Market Scales (SQUIDs)

Calendar year →

1990 2000 2010 2020 2030

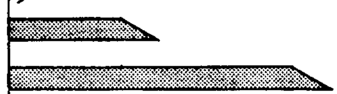
(1) Metallic superconductors

(Technical forecasts)

- Completion of a practical material
- Completion of a prototype

} Already finished

- Completion of a test system for demonstration
- Commercialization



(Market scale)

Commercial-ization	Initial market	10 years later	20 years later
-1997	¥ 200,000 5 units/year	¥ 2.5 million 50 units/year	¥ 5 million 200 units/year
-2000	¥ 1 billion	¥ 10 billion 10 units/year	¥ 10 billion 100 units/year
1995–2005	¥ 10 million 1 unit/year	¥ 100 million 10 units/year	¥ 25 billion 500 units/year

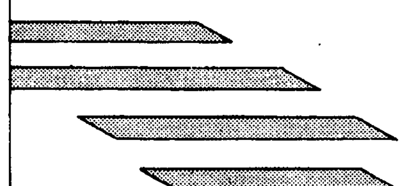
Calendar year →

1990 2000 2010 2020 2030

(2) Oxide superconductors

(Technical forecasts)

- Completion of a practical material
- Completion of a prototype
- Completion of a test system for demonstration
- Commercialization



(Market scale)

Commercial-ization	Initial market	10 years later	20 years later
2000–2010	¥ 100 million 5 units/year	¥ 5 billion 100 units/year	¥ 50 billion 1,000 units/yr
1995–2000	¥ 200,000 5 units/year	¥ 5 million 1,000 units/year	¥ 1 billion 2,000 units/yr

b) Oxide SQUIDs

- **Technical forecast**

A Ti-based SQUID that operates at 77 K has been developed, but all the SQUIDs developed so far including the Ti-based device are based on grain boundary junction technology, so they have far to go in terms of property control. However, once Josephson junction technology is established, with some ingenuity in the designs of detection coils and input coils, oxide SQUIDs are expected to hit the market relatively early. Dr. (Basiryev) at the Joint Atomic Nucleus Research Institute in the USSR has succeeded in measuring magnetism in the heart using a SQUID based on superconductors, although details of how the device was fabricated and what level of repeatability it possesses are not known. However, for SQUIDs to reach the level of sophistication that enables them to measure magnetic fields in the brain, many technical difficulties remain, including establishing lamination technology.

- **Market scale**

Many unheard-of technical tasks await solutions, and at this stage where the question is if SQUIDs will ever become commercial products, it is very difficult to forecast the market scale for them. The market forecasts are based on the assumption that Josephson junction devices will reach the stage of technical accomplishment. In the initial stage of their development, SQUIDs may be used in nondestructive testing and in measuring fields where the job could be done using less sophisticated devices than those used to measure magnetic fields in the brain. Such uses could include measuring the magnetic fields in the heart or the lungs.

- **Prospects for technical development**

The technologies needed for SQUIDs, such as the Josephson junction-forming technology, microprocessing technology, and lamination technology of oxide superconducting materials, have yet to be established, and hence it is difficult to forecast when SQUIDs will be commercialized. However, great expectation is placed on SQUIDs for the reasons that the simple refrigeration method facilitates handling and that systems using SQUIDs can be built in a small and compact configuration.

2) Future Priority Tasks

a) Technical tasks

- In the use of SQUIDs as medical systems, the important technical tasks are multichanneling and developing diagnosing software.

- As for oxide SQUIDs, the first priority should be research into the basic practical material that satisfies the requirements for repeatability, reliability, and stability. To be concrete, the tasks are understanding the phenomenon on the junction interface, forming the superconductor-insulator-superconductor (SIS) type of Josephson junctions, eliminating magnetic flux traps, and forming thin-film "gradiometer."

b) Social and economic tasks

It is not clear how many needs exist for SQUIDs incorporating oxide superconductors. It is necessary to expand the needs by clarifying the scope and level of applications to which SQUIDs can be used, as well as their advantages. To that end, it is important to develop superconducting materials of high reliability.

c) Required peripheral technology

• **Cooling technology**

At this stage where room-temperature superconductors are not available, superconductors must be refrigerated. For superconductors to find ready use, a method would be to use them in a lightweight and compact refrigerator. The technology of such refrigeration is well established, such as electronic refrigeration. When considering the use of such a refrigerator with a SQUID, the problems are vibration and nonmagnetization. Once development is started, a commercial refrigerator will appear on the market in several years.

• **Junction technology**

Connections between devices and the circuits that are kept at room temperatures are reduced to the problem of connections between superconductors and metals like copper wire. The junction problem exists in the case of metallic devices, but the issue is solved by pressure deposition or spot welding. Such technologies are not applicable for existing oxide superconductors. A practical junction technique will be developed in about 10 years.

• **Shielding technology**

The more sophisticated a device is in terms of performance, the stronger its demand will be for shields with higher shielding capabilities. Several shields of various performance are on the market. The highest performance shielding technology, the shield room using high-magnetic permeability devices, is expensive. Shields using high-temperature superconductors are at the research stage.

3) Conditions Needed for Realization

a) Needs

A great expectation is placed on medical SQUID systems for diagnosing functional abnormalities. The needs for SQUIDs will further increase if SQUID systems can be used with a refrigerator or if their structures are simplified by using refrigeration with liquid nitrogen, leading to cost reductions.

b) Role of government

The government should assist research on a continuous basis with a long-term perspective. Standards should be established, under which the use of SQUIDs as medical apparatuses would be permitted. To that end, cooperation must be maintained between the Ministry of International Trade and Industry and the Ministry of Health and Welfare.

c) Research structure

Parallel research on both oxide and metallic SQUIDs should be promoted.

d) Personnel

SQUIDs proper have been developed by engineers in the fields of physics and electronics. However, when development of medical systems incorporating SQUIDs is undertaken, it will be necessary to have the cooperation of researchers and engineers from a variety of disciplines including medicine, neurophysiology, and data processing, in such areas as the analysis of the sources of magnetic fields, data processing, and display.

e) Reliability and safety

Measuring the magnetic fields in the body using a SQUID is noninvasive measuring, so the diagnosis is safe in principle. However, if SQUIDs are used for medical purposes, they should meet some standards. Such SQUIDs, oxide as well as metallic ones, would need a low-temperature environment, and special attention must be paid to the safety of the cooling systems.

f) International cooperation and competition

Judging from the developmental scale, there would be no special need for an international cooperative structure. In the United States and Europe, development of systems incorporating metallic SQUIDs is already progressing. Though the market is small, the possibility for international frictions should be kept in mind.

g) Comparison with competing technologies

Flux gate magnetometers and Hall elements are being used as the sensors for low magnetic fields, but only SQUIDs can measure extremely weak magnetic fields. Since SQUIDs as medical apparatuses can locate functional abnormalities, they have no competitors.

h) Social environment

Efforts must be made to widely disseminate the technique for high-level measuring of magnetic fields in the body, especially to foster acceptance of the technique by medical researchers.

4) **Scenario for Realization**

Development of high-reliability junctions ↓ Development of lamination technology	Use of measuring and circuit technology and cooling technology	Demonstration testing for use as medical apparatuses
↓	↓	↓

↓

Compact SQUID system

5) **Impact on Society and Economy**

When SQUIDs have been commercialized as medical apparatuses, they will be used in hospitals but the market for them is limited.

6) **Others**

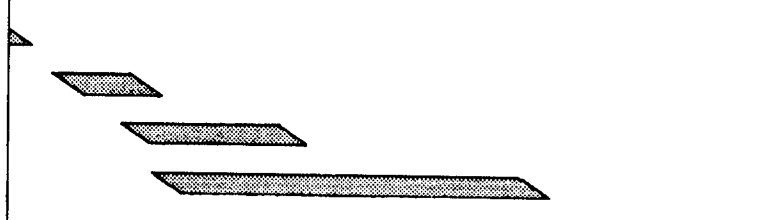
SQUIDs as systems are believed to have an expanded scope of applications if they are used with a small refrigerator rather than if they are refrigerated using liquid nitrogen, and this would raise their capacity to cope with various T_c levels.

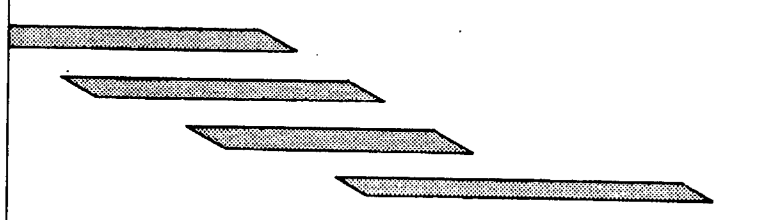
(2) Josephson Junctions

Five answers were obtained on the question about the future movements of Josephson junctions. Josephson junctions have been used widely in both analog applications, such as SQUIDs, voltage standards, and submillimeter wave detectors, and digital applications, such as switching devices in logic circuits. In making a technical forecast, it is necessary first to define the device or system into which Josephson junctions are incorporated. In this report, the results of the questionnaire are sorted centered on the Josephson computer, an application that has long been viewed as highly promising and that involves large-scale R&D. A great expectation is placed on the Josephson computer as the next-generation computer. Superconductors, the theme running through the entire spectrum of the current questionnaire, are used in the major functions of high-speed signal processing in Josephson computers. These include switching devices in logic, memory, and peripheral circuits, interconnects for devices on a chip, and interconnects for packaging.

Table 2.2-9 gives the results of the technical forecasts and market scales for both metallic and oxide Josephson junction devices. The left side of the arrow shows the most optimistic forecast while the right side gives the pessimistic forecast. As for oxide Josephson junctions, some respondents left the entry for their commercialization period blank for the reason that forecasting the period is impossible.

Table 2.2-9. Technical Forecasts and Market Scales (Josephson junction devices)

	Calendar year → 1990 / 2000 / 2010 / 2020 / 2030			
(1) Metallic superconductors (Technical forecasts) • Completion of a practical material • Completion of a prototype • Completion of a test system for demonstration • Commercialization				
	Commercial-ized	Initial market	10 years later	20 years later
(Market scale)	1996–2020	¥ 10 billion	¥ 100 billion	¥ 1 trillion

	Calendar year → 1990 / 2000 / 2010 / 2020 / 2030			
(2) Oxide superconductors (Technical forecasts) • Completion of a practical material • Completion of a prototype • Completion of a test system for demonstration • Commercialization				
	Commercial-ization	Initial market	10 years later	20 years later
(Market scale)	2005–2030	¥ 10 billion	¥ 100 billion	¥ 1 trillion

1) Technical Forecasts and Market Scales

a) Technical forecast

As for metallic systems, the practical material (Nb) and the Josephson junction ($Nb/AlO_x/Nb$) have already been developed. The development now is in the stage of upgrading of the LSI technology and trial manufacture and evaluation of a prototype. The Josephson computer has already been confirmed to function in its basic capabilities, and development is now under way on a processor that operates at a high-speed clock time and a memory circuit of a 4K-bit scale. After going through the development of a prototype and its testing for demonstration, a commercial Josephson computer is forecast for the 1995 to 2020 period. Most of the answers say commercialization will take place in the year 2000 or later. Many tasks must be solved before a Josephson computer is realized, such as increased integration and development of peripheral technologies. The process technology for Josephson LSIs is based on the semiconductor technology but a fairly large number of peripheral technologies that must be developed still remain. Regarding the functional reliability of Josephson junctions, problems are inherent with the devices, such as the flux strap and punch-through phenomena. Add to these technical tasks the social and economic tasks, such as the superiority of the Josephson computer over the supercomputer in performance and the actual developmental cost, and it is no wonder that a large gap of 25 years exists between the most optimistic and the most pessimistic predictions for commercialization of the Josephson computer.

As for oxide Josephson junctions, a gap of more than 15 years exists between optimistic and pessimistic predictions when the practical material for Josephson junctions will be developed. The majority opinion is that such a material will be realized by the year 2000 or so. The answers were varied, with some forecasting the commercialization before 1995, while others saying it is difficult to forecast since the development is still in the basic research stage. If the Josephson computer is to be operated at liquid nitrogen temperature, the oxide superconductor will have to possess a critical temperature of at least two times the operating temperature of the computer, i.e., above 150 K. However, no material has yet been developed that meets the above requirement. Given the properties of the oxide superconductors that have so far been discovered, it would hardly be possible to develop tunneling-type Josephson junctions. About 15 years will be needed before a prototype is developed and a test machine for demonstration testing is developed, and the development of a commercial machine is forecast for 2005 to 2030. It is difficult to forecast when the practical material will be developed or when the technology for fabricating the material into devices will be accomplished, but given the fact that many of the technologies developed during the development of metallic Josephson junctions are applicable in the process and circuit technologies for oxide Josephson junctions, once the basic technologies are accomplished, technical tasks surrounding the commercialization of oxide Josephson junctions might be solved earlier.

b) **Market scale**

For the Josephson computer to find a market, the practical use machine would have to possess a high-speed performance capability that is more than 10 times larger than that of its competitor, the semiconductor-based supercomputer. The Josephson computer is expected to find use as an extension of the semiconductor supercomputer, and the initial-year market is anticipated to be several units per year. The demand is forecast to increase by more than an order of magnitude every 10 years. Based on the costs of semiconductor supercomputers, the Josephson computer with an increased performance capability is expected to cost between several hundred million yen to ¥1 billion.

In the Josephson computers based on oxide superconductors, changing their operating environment from refrigeration by liquid helium to refrigeration by liquid nitrogen is expected to bring about advantages in the forms of a compact refrigerator and reduced costs, and the market for such machines is forecast to be about the same as that for Josephson computers based on metallic superconductors.

2) **Future Priority Tasks**

a) **Technical tasks**

As for the Josephson computer incorporating Josephson junctions based on metallic superconductors, the development is at the stage of trial manufacture and prototype evaluation. However, many technical tasks remain before the Josephson computer will be produced commercially. Among the tasks associated with the process are increased integration and an improved process so that the circuit parameters will be controlled at an elevated level of high precision. Among the tasks associated with circuits are the development of a high-density packaging technology that will diminish propagation delays of exceptionally high-speed signals, and a high-efficiency refrigerating technology that will enable the machine to work for long hours at low temperature. Refrigerators for such a use have been developed, but none has yet met the requirements for practical use, such as small size and freedom from maintenance. For the Josephson computer to be able to display its high-speed performance capability to the fullest, it is extremely important not only to upgrade the LSI technology but also to develop the system optimization technology such as parallel data processing.

In the case of the Josephson computer using Josephson junctions based on oxide superconductors, the R&D of the practical material must be completed before the solutions of the technical tasks associated with the metallic superconducting Josephson computer can be undertaken. For Josephson junctions to be able to operate stably at liquid nitrogen temperature, development of a material with a critical temperature above 150 K is needed. Given the properties of the existing oxide superconductors, such as the instability of crystals and short coherence length, it is assumed the realization of an oxide tunneling-type Josephson device will be very difficult. Independent technical development is also needed in the field of integration technology, such as lamination and microprocessing. Flux trap may prove to be a problem of much higher importance than it is for metallic Josephson junctions.

b) Social and economic tasks

As society becomes more information oriented, the demand for supercomputers will also increase, but for the Josephson computer to see practical use, it must meet the following conditions: possess the performance capabilities demanded by the society; and surpass the semiconductor supercomputers by more than an order of magnitude in high-speed operating capability.

3) Conditions Needed for Realization

a) Needs

The burgeoning highly advanced information society will have an increasing demand for supercomputers. But whether a demand for Josephson computers will emerge will be determined by how much superiority they will retain over their competitors, semiconductor supercomputers.

b) Role of government

Thanks to the government's policy measures, the development of the integration technology of Josephson junctions based on metallic superconductors has progressed greatly, but government assistance is continuously needed since the technology for packaging these integrations together as a system has yet to be developed. The government is also expected to make efforts to unify software technology including operating systems. As for oxide superconductor-based Josephson junctions, the development is at the basic research stage, in search of practical materials and device fabrication technology, and characterized by a strong uncertainty, so appropriate government policy measures are needed.

c) Research funds

Since developing a Josephson computer is a large-scale, long-term research project, the government is required to render its assistance. In the case of the Josephson computer based on metallic Josephson junctions, the government is expected to spend more than ¥10 billion to develop a demonstration machine, and in the case of the Josephson computer based on oxide Josephson junctions, the government is expected to provide the private sector with more than ¥5 billion for research consignments.

d) Research structure

Since the research is long-term, a government-private monolithic refrigeration structure is desired.

e) Personnel

Thanks to the government's policy measures, excellent researchers have been trained in developing metallic Josephson LSIs. For raising the efficiency of R&D, it is necessary to continue personnel exchanges between academia, government, and industry.

f) Reliability and safety

Since the Josephson computer is used in a low-temperature environment, it is most important that the reliability and safety of its refrigerating equipment is maintained.

g) International cooperation and competition

Japan is leading the world in researching metallic Josephson LSIs, so it is in a favorable position to extend international cooperation.

h) Comparison with competing technologies

Among the technologies competing with the Josephson computer technology are those of Si and GaAs supercomputers. Of the two, silicon supercomputers, in particular, are a good competitor, in light of their good track record and their processing speeds that have improved beyond expectation.

i) Social environment

In the information era when large amounts of data are processed at high speeds, the expectation for the debut of a supercomputer having performance capabilities not previously seen is great. At present, the social environment prohibits application of low-temperature devices to the Josephson junction computer.

4) Scenario for Realization

In the case of the Josephson computer based on metallic Josephson junctions, the tasks are the development of the required technologies in such fields as high-level integration, high-precision process control, high-speed clocking, packaging, and high-efficiency refrigeration and the manufacture of a small-scale system for demonstration. While the developmental efforts are being made, basic research will be conducted to realize a Josephson computer based on oxide Josephson junctions, in such areas as the elucidation of physical properties. Efforts will be made to develop a practical material and the technology for fabricating the material into devices. As for the integration of oxide Josephson junctions into LSIs, the technology obtained in integrating metallic Josephson junctions into LSIs will be employed. When tasks inherent in oxide Josephson junctions have been solved, a small-scale system incorporating oxide Josephson junctions will be realized.

5) Impact on Society and Economy

The development of a Josephson computer having more than 10 times the processing capabilities of semiconductor supercomputers will lead to a widespread use of simulation technology and superlarge databases in the fields of science and technology, thereby making a great impact on society and the economy.

(3) Three-Terminal Devices

Four answers were obtained on the future trends of three-terminal devices.

1) Technical Forecasts and Market Scales

The results of technical forecasts and market scales obtained in the questionnaire survey are given in Table 2.2-10.

a) Technical forecasts

• As with Josephson junctions, in three-terminal devices controlling the junction interfaces between superconductors and semiconductors involves much difficulty, so it will be a long time before superconducting three-terminal products appear on the market. Even metallic three-terminal devices have yet to obtain power gains that are high enough to make their use in practical applications feasible. Even when a practical material has been developed, the lead time from the development to the completion of a prototype will be much longer than the comparable time for Josephson junctions.

• The proposed three-terminal devices are of two types: one a structure which, although low in performance capability, operates smoothly and the other a structure which, although its performance has yet to be fully demonstrated, promises a high performance capability. Therefore, a three-terminal device that can withstand practical use has yet to be explored in terms of both structure and function. Although the elucidation of the mechanisms of high-temperature superconductors may accelerate the research, three-terminal devices are a long-term research project.

• In metallic three-terminal devices, elucidating their principle and fabricating them into devices that obtain gains readily may take a long time. Devices with a higher T_c are advantageous in terms of band gap, and they may be realized early.

• It is difficult to forecast the technology at the stage where it has succeeded in testing its principle, but the technology is positioned as supplementing the post Josephson junction era.

b) Market scale

• It is difficult to forecast the market scale. The reasons are: 1) the performance of semiconductors and their market scale in 10 to 20 years are unknown; and 2) the targeted performance of a three-terminal device relies on its principle and structure.

• The scale of the market is calculated based on the demand for supercomputers.

• The scale of the market is forecast based on the assumption that supercomputers will find some specific uses.

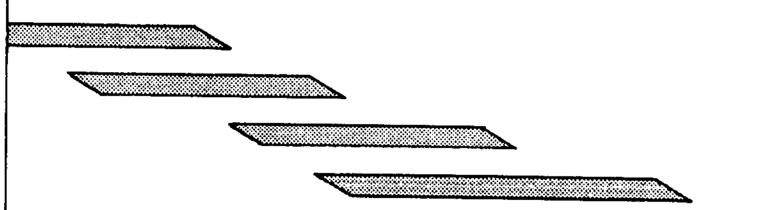
Table 2.2-10. Technical Forecasts and Market Scales (Three-terminal devices)

Calendar year ⟶ 1990 | 2000 | 2010 | 2020 | 2030

(1) Metallic superconductors

(Technical forecasts)

- Completion of a practical material
- Completion of a prototype
- Completion of a test system for demonstration
- Commercialization



(Market scale)

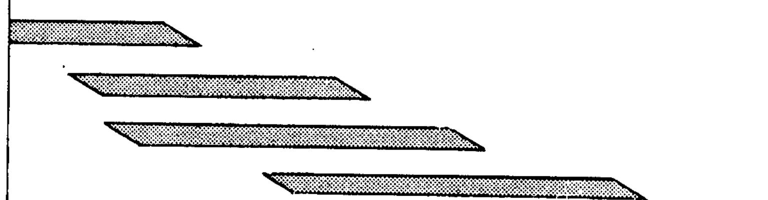
Commercial-ization	Initial market	10 years later	20 years later
2015−2030	¥ 35 billion	¥ 1 trillion	¥ 1.5 trillion
2010−2020	¥ 10 billion	¥ 100 billion	¥ 1 trillion

Calendar year ⟶ 1990 | 2000 | 2010 | 2020 | 2030

(2) Oxide superconductors

(Technical forecasts)

- Completion of a practical material
- Completion of a prototype
- Completion of a test system for demonstration
- Commercialization



(Market scale)

Commercial-ization	Initial market	10 years later	20 years later
2002−2012	¥ 35 billion	¥ 1.5 trillion	¥ 3 trillion

c) Technical prospects

• The forecast is the same as that in the technical forecast. Once the principle and structure are decided, it will not be long before the technology becomes practical. Most of the technology is the same as the semiconductor process, and some aspects of the semiconductor design methodology may be applicable in the design of the three-terminal device.

• An important task is the solution of the principle.

• Experiments are needed to test the principle of the three-terminal device as a switching device. That is, once the development of a Josephson junction with three terminals has been accomplished successfully, the technology for integrating such devices must be developed.

d) Where superconductors will be used in systems

• Electrodes for three-terminal devices, interconnects, grand planes.

• Parts of electronics using superconductors.

• Central processing units (CPUs).

• Parts where high-speed processing is needed in a system.

e) Schematic specifications

• The same level as semiconductors in terms of power gains (several 10~100 dB)

• Areas where the objective cannot be realized with semiconductors, and breakthroughs in functions that are beyond the processing, physical, and thermal limits and that cannot principally be realized.

• Capabilities above 13 giga floating operations per second (GFLOPS).

• An expected performance capability more than 10 times that of a silicon semiconductor computer.

2) Major Tasks in the Future

a) Technical tasks

• Understanding of interface control technology and interface phenomenon; low-temperature film growth technology.

• The superconducting three-terminal devices have not yet been proven to have an operating capability above their semiconductor counterparts. There is a great gap in the concept between cryogenic temperature and cooling. A three-terminal device based on a new principle and structure must be developed using a high-temperature superconductor.

• i) Device physics (device performance, multifunctionality); ii) integration technology; iii) package technology of superconductors.

b) Social and economic tasks

• Comparison of the performance of the computer demanded with the performance of a similar computer based on other devices.

• Devices using semiconductors, especially Si, have achieved rapid progress. Interchangeability on the level of modules, including the operating environment, is desired. A widespread diffusion of superconducting devices on the strength of their use as devices in their own right (such as sensors).

c) Peripheral technologies needed for practical use: i) reason; ii) current state; iii) period)

• 1) Package technology—i) The establishment of the technology as a system is indispensable; ii) the metallic Josephson device technology should be taken advantage of.

2) Interface—i) The establishment of the technology as a system is indispensable; ii) the interface between 4.2 K Josephson junctions and semiconductors is being developed; iii) this development should be completed in three years.

• Signal input/output, cooling technology (for realizing a module), packaging method. Only prototypes. Although it will depend on demand, the pace of development will not be slower than that of the three-terminal device.

• The development of Josephson memories will go hand in hand.

• Josephson junctions device matches.

3) Conditions Necessary for Practical Use

a) Needs

• Data processing as ultrahigh speeds.

• When the limits of the silicon integrated circuitry in terms of capabilities (heat, speed, etc.) become apparent.

• High-speed digital and analog applications.

b) Role of government

• Since the risks of investment are high, the research should be undertaken as a national project.

• Government needs to generate as large a demand from the creative research sectors (space, ocean development, etc.) as the United States generates from the military.

• Superconducting three-terminal devices based on oxide superconductors are still at the research stage on the concept of the device, so the research contains much unknown territories. Consequently, the needs for government assistance are strongly felt.

c) Research funds

• Several ¥10 billion.

• Cooperation between academia and industry; accumulation and publicity of information.

• ¥6 billion over 10 years.

d) Research structure

• Judging from the scale of the development, a cooperative research structure involving national and public research institutes and businesses is needed.

• Collaboration between academia and industry; accumulation and publicity of information.

• The existing research structure is the most desirable one.

e) Personnel

• Recruiting researchers and engineers in the fields of physics and electricity is necessary.

• Recruiting people who are strong in both engineering and theory of semiconductors is necessary.

• Training of personnel is progressing smoothly thanks to the government's policy.

f) Reliability and safety

• Reliability will follow when the stability of oxide superconductors has been established.

• As for safety, nothing is known yet.

g) International cooperation and competition

• Maintaining international cooperation is desired.

• International cooperation should be extended by opening to the world basic research achievements, personnel exchanges, and shared databases.

• Exchanges through international symposia are more desirable than international cooperation.

h) **Comparison with competing technologies**

• Competition with semiconductor devices (high speed, low power consumption).

• How to cope with the trends toward the modular construction of electronics as a whole.

• Silicon semiconductor devices, metallic Josephson junctions.

i) **Social environment**

• Processing of signals at ultrahigh speeds.

• How to break through systems designers' tendencies to opt for the proven technology.

4) Scenario for Realization

• Low-temperature film-making technology + microprocessing technology + interface control technology + lamination technology + package technology + interface technology + cooling technology = superconducting signal processing system.

• 1) Elucidation of the superconducting mechanism:

—Upgrading the material → crystal growth and measurement of properties
—A search for materials on a systematic basis
—A switch in the tactics from "trying everything that comes along."

2) The use of technology and knowledge of semiconductors.

3) The use of simulation.

• Clarification of the principle → increased gains → IC technology → combination with Josephson memories.

• Researching and fostering new functional devices that belong technologically to untrod areas is always unfathomable, and herein lies the need for government's aid. The government is expected to continue assistance in line with its current policy measures.

5) Impact on Society and Economy

• Science and technology fields where data must be processed at high speeds.

• 1) Contribution to the growth of systems x high-level integration (small size), high speed, low power consumption.

2) Expanded use of resources x the use of submillimeter waves in the far infrared zone.

3) Control of the superconducting power applications.

• The impact is the same as the one in the case of Josephson junctions. Its use in supercomputers will have an impact.

• As the next-generation device replacing Si semiconductors, its impact on society and the economy will be great.

(4) Wiring

Five persons answered the question on the future trends of interconnects. The returns of the survey and the results of their analyses are given below.

1) Technical Forecasts and Market Scales

Table 2.2-11 gives the results of the questionnaire survey on technical forecasts and market scales.

a) Technical forecasts

• 1) There is no problem with material properties as long as the superconductors are used at liquid helium temperature. However, from the perspective of cost versus performance, there is no prospect for their use in the wiring of devices.

2) As for superconductors' uses as interconnects between devices on a chip, such an interconnect will become necessary in devices of more than 100 megabits in memory capacity. It will be about 10 years before such an application will be realized. The use of superconducting interconnects for chip-to-chip connections and packaging will be five to 10 years from now although it will be determined by when the low-temperature cooling device is realized.

• 1) It is forecast that superconducting interconnects will be used only in circuitry using metallic superconducting devices. Oxide superconductors will take over as superconducting interconnects.

2) The development of circuitry using superconducting devices and circuitry partially using superconducting devices, as well as the development of a small-size refrigerator of low power consumption will lead to the use of superconductors as interconnects in LSIs.

• According to some calculations, there are no advantages in using superconductors as interconnects between devices on a chip and between chips on each other. Therefore, there will be no merits in using superconducting wiring until superconducting electronics are commercialized.

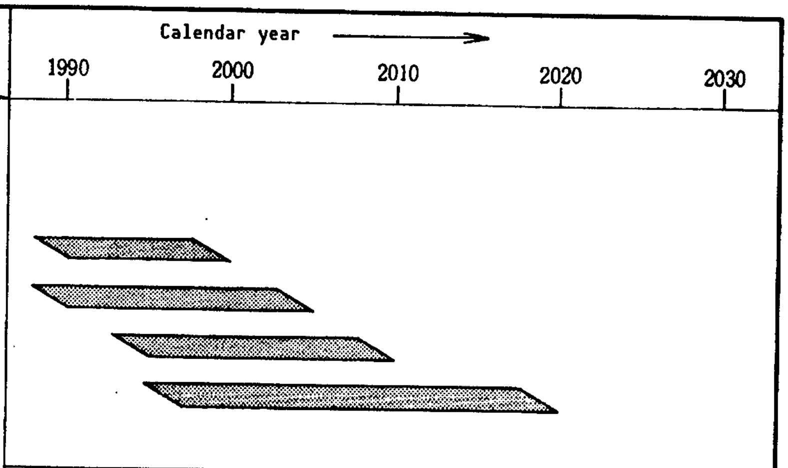
• 1) Superconducting wiring will be realized early, but the market will be small because the technology requires a larger refrigeration system.

Table 2.2-11. Technical Forecasts and Market Scales (Wiring)

(1) Metallic superconductors

(Technical forecasts)

- Completion of a practical material
- Completion of a prototype
- Completion of a test system for demonstration
- Commercialization



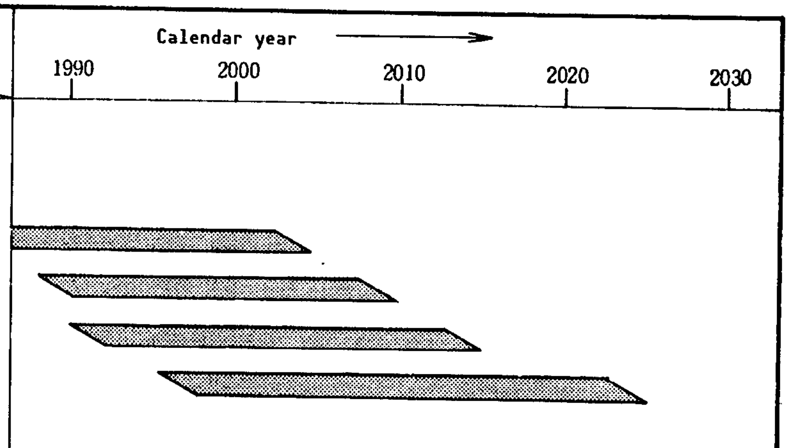
(Market scale)

Commercialization	Initial market	10 years later	20 years later
2010–2020	¥ 10 billion	¥100 billion	¥ 1 trillion
1997–2002	¥ 100 million	¥ 1 billion	¥ 1 billion
2003–2010	Unknown	Unknown	¥ 1 billion
2000–2005	¥ 10 million	¥ 250 million	Less than ¥ 100 million

(2) Oxide superconductors

(Technical forecasts)

- Completion of a practical material
- Completion of a prototype
- Completion of a test system for demonstration
- Commercialization



(Market scale)

Commercialization	Initial market	10 years later	20 years later
2005–2015	¥ 10 billion	¥ 100 billion	¥ 1 trillion
2015–2025	¥ 10 billion	¥ 100 billion	¥ 1 trillion
2002–2020	¥ 10 billion	¥ 50 billion	¥ 50 billion
2015–2020	¥ 250 million	¥ 25 billion	¥ 25 billion
1997–2004	¥ 1 million	¥ 100 million	¥ 100 million

2) It will be some time before the material is realized and a practical system incorporating the material, including its cooling system, is commercialized, but the market is large.

• Nonmetallic superconductors are the target of study for use as interconnects. Only those that operate at liquid nitrogen temperature will find use as interconnects.

b) Market scale

• 1) As for the application of metallic superconductors for wiring, the development will proceed as far as demonstration tests, but whether such interconnects will be commercialized is unknown.

2) As for oxide superconductors, provided they can be cooled using liquid nitrogen, they will find use in a limited field of leading-edge technologies, such as supercomputers, satellites, and the military, and the market will not be so large.

• System incorporating superconducting devices are limited to a few special equipment, such as MRIs, supercomputers, and ultrahigh-precision measuring instruments. LSI wiring is employed in high-level measuring instruments. Since the current market for LSI circuits is ¥220 billion, superconducting wiring will be adopted in 10 percent of the circuits.

• As for the practical use of superconductors in wiring, superconducting interconnections will not be commercialized before the following conditions emerge: 1) technical innovation of semiconductor devices comes to a near standstill; 2) systems using semiconductor devices reach technical limits; and 3) superconducting electronics are used on a full-fledged basis.

• 1) It will be difficult for the superconducting interconnects to penetrate the current market for semiconductors and packages, and they will only be able to find a special niche field.

2) Superconducting interconnects are expected to find about 10 to 20 percent of the current market (~several ten billion yen).

• The cost of substrates for packaging is 10 percent of the supercomputer.

c) Prospects for technical development

• 1) With liquid nitrogen cooling as a precondition, development of a material with a higher T_c, a minimum of 150 K, is needed. Providing for an allowance, J_c is needed to be at least $10^7 A/cm^2$.

2) Development of fabrication technology of interconnects and of ultramicro-processing technology is needed. An increase in investment into basic technical tasks such as the study on the reliability of material is necessary. Investment in basic research into breakthrough technologies for large-capacity and high-speed computers needs to be made continually.

• As for metallic superconductors, there will be no problem with them since the LSI wiring technology is applicable. As for oxide superconductors, activity will be mainly in the development of new materials and their manufacturing process.

• Innovations of semiconductor devices will hit a deadlock in 10 to 20 years, but it will be 10 to 30 years after that that the systems design using those devices will hit a deadlock. Until that time comes, superconductors will find little use. However, when there is a compelling demand, the superconductor technology will see a rapid increase.

• Since the development of a superconducting interconnect will progress hand-in-hand with the development of a supercomputer that operates at liquid nitrogen temperature, development of devices that operate at 77 K is necessary.

d) Parts of the system where superconductors are used

• Interconnects for devices on a silicon LSI chip and interconnects for transmission of signals between chips (high-speed computing and processing systems), microwave communications systems, satellite transponders.

• Interconnects in a device and between devices.

• Interconnects in a chip and between chips.

• CUP [as published] and its peripheral devices in a high-speed calculator.

• Substrates for supercomputers, package interconnects for devices that operate at 77 K.

e) Schematic specifications

• Supercomputers—10 GFLOPS at present, 100 GFLOPS five years later, and 1 tera floating operations per second (TFLOPS) 10 years later. The requirements for the wiring material are $T_c \sim 150$ K and $J_c \sim 10^7 A/cm^2$.

• $J_c > 10^7 A/cm^2$, pattern width < μm.

• Devices of about the same size as semiconductor devices that have higher levels of integration (more than 256M bits in memories) and higher speeds (gate delay time of less than 1 ps).

• Current density of $10^6 A/cm^2$ (when mounted on the substrate).

2) Major Tasks in the Future

a) Technical tasks

• Materials technology (investments need to be made on a continual basis to develop a material with a high T_c, the technology for gaining a high J_c, and seeds technology), machining process (high-quality thin film manufacturing

technology, ultrafine lithography technology), materials evaluation technology, cooling technology (development of low-cost refrigerating technology).

• Oxide superconductors (technology for making thin films of single crystals at temperatures below several 100°C, technology for processing thin films).

Solutions: Clarifying the mechanism of the crystal growth of oxide superconductors, and the discovery of the conditions for crystal growth at low temperature, probing for a new material. At this stage of development, the best way to find a solution is to try to accumulate data steadily.

• It is not so much the technical task associated with wiring as the task associated with the technology for practicalization of superconducting integrated circuits beginning with high-integration and superhigh-speed Josephson junctions.

• Workability, corrosion resistance, and contact characteristics for the whole wiring system including the substrate.

• The superconductor must be superior to existing metals in terms of high frequency and high-speed signal transmission characteristics. In wiring, a dielectric layer is essentially needed and developing the technology for laminating the superconductor with the dielectric layer is the key.

b) Social and economic tasks

• The progress of an information-oriented society 10 years from now will generate an increasing demand to process large amounts of information at high speeds. It is necessary to establish a system under which investment funds needed to develop new technologies will flow in continually.

• It is desired that assistance be provided for research projects that involve risks, from a long-term perspective.

• Semiconductor technology will hit a deadlock sooner or later. It is necessary to try to instill the fact that only superconducting electronics have the potential to overcome the difficulty. Efforts should be made to turn systems designers and researchers toward superconducting devices.

• Once superconducting wiring technology is demanded from the levels of workstations, in addition to the mainframes, the market will expand.

c) Peripheral technologies for practical use: (i) reason; (ii) current state; (iii) when

• Low-temperature devices: (i) device manufacture; (ii) development of a demonstration system; (iii) ~1995.

> Microprocessing: (i) lithography technology below 0.1 μm; (ii) research on 0.25 and 0.1 μm; (iii) ~2000.

CAD technology: (i) design of large-scale devices; (ii) the technology for devices below 100M-bits is unknown; (iii) ~2000.

Refrigeration technology: (i) low-cost operation of equipment; (ii) the equipment is too large and expensive; (iii) ~2000.

• Low power consumption, low cost, ultrasmall refrigerator, insulation package technology: (i) these features need to be incorporated into the system for bonding with peripheral systems; (ii) a panel-type cooling device (80 K) is on the market; (iii) about 10 years.

• Superconducting electronic systems: (i) the advantage can be found only in superconducting electronics; (ii) 4K-bit memories and 4-bit microprocessors; (iii) 30 years later at the earliest.

• Small refrigerator technology: (ii) although floor-type refrigerators are developed, console or assembly type ones are still at the development stage; (iii) several years later.

• Devices that operate at liquid nitrogen temperature: (i) superconducting wiring is effective only under refrigeration; (ii) some devices, refrigerated, are finding practical use in such applications as infrared sensors, but ICs of silicon devices that operate at liquid nitrogen temperature have yet to be developed; (iii) a trial computer that operates at liquid nitrogen is scheduled for completion in 1995.

3) Conditions Necessary for Practical Use

a) Needs

• The requirements for new devices to cope with power consumption as a result of increasing high-speed operations of super LSIs and their micropatterning.

• An increase in the demand for systems incorporating superhigh sensitivity and superhigh-speed devices, and the requirements for devices that exceed the speed limits of existing LSIs.

• The limits of systems incorporating semiconductor devices, or the development of consumer systems whose jobs only superconducting electronics can perform. At present, the fields will be limited to the military, space, and astronomy.

• Will find uses in the packages of existing high-speed devices, before computing systems incorporating high-speed devices based on oxide superconductors are developed.

• Inevitably needed in high-speed computers.

b) Role of government

• Implementation of measures is needed to cope with the burden of increasing funds for investment into technical development, expansion of national projects, and establishment of a legal system that treats investments into basic research as tax deductible expenses.

• The government is required to establish a model target so that a collaborative body of the national and public research institutes, universities, and corporations will be able to work on it for its realization.

• A long-term research assistance structure is needed.

• A project for the "development of a computer that operates at low temperature" must be started, and it should be a comprehensive project involving research in such fields as refrigeration, wiring, and devices.

c) Research funds

• An increase in the research funds allocated to the national and public research institutes is needed.

• The establishment of a long-term research assistance structure is needed.

• If superconducting wiring is to be used on a full-fledged basis, research equipment that is larger than the existing equipment for semiconductor research will be needed, but it is premature to place an expectation on the technology until a prospect for its commercialization appears.

• In the field of basic research, the capabilities of the private sector to conduct research have limits.

d) Research structure

• Increased cooperation between industry, government, and the universities is needed.

• Collaboration between industry and the universities is needed.

• Until the technology nears commercialization, it is desired to let the researchers have a large degree of latitude in their research and expect new findings to emerge from their fresh ideas.

• A joint research structure involving industry, government, and the universities, with a special emphasis on the private sector is needed.

e) Personnel

• Personnel exchanges between industry, government, and the universities, and giving a momentum to the exchanges by establishing a system under which personnel are exchanged on a short-term basis between industry and the universities and between industry and government.

• Add to the ranks of researchers those who have been engaged in the development of LSIs.

• The question of how many talented personnel to be diverted to the research.

f) Reliability and safety

• It is duly expected that a full evaluation testing will be conducted before the technology is commercialized.

• The technology is required to have about as much reliability and safety as for electronic parts on the market.

g) International cooperation and competition

• International cooperation in basic research is needed.

• Active cooperation should be extended, provided the other party does not take a closed-door policy.

• With the exception of the academic field, there will be no need for full-fledged competition to be waged for some time. The competitors are the semiconductor device systems.

h) Comparison with competitive technologies

• The requirement is to overcome the technical limits of semiconductor devices.

• The growth of LSI technology beyond the current expectation is seen.

• As far as semiconductor devices are concerned, it is impossible for superconductors to replace Al or Cu.

• For use as wiring material, superconducting wire is more effective than metals.

i) Social environment

• The environment should be relaxed enough to give researchers room to engage in basic research.

4) Scenario for Realization

a) Investment in research to promote basic technology: several ten billion yen

Funds to promote cooperative research with foreign research organizations: several billion yen.

Establishment of a foundation to promote and assist testing of new technologies for commercialization.

Development of commercial superconducting technology under a national project.

b) Establishment of thin film forming and processing technologies (growth and processing of films at temperatures below several hundred °C and their lamination on a semiconductor substrate)

Low-temperature package technology: establishment of superconducting LSIs.

c) As long as systems based on semiconductor devices do not stop making progress, the prospects are very slim for superconducting electronics or part of these electronics, superconducting wiring, to be commercialized for some time, except for special uses in niche fields with a small market. However, depending on new discoveries or inventions, their forecast may turn out to be wrong.

d) Superconductors will gradually be used in wiring devices that operate at liquid nitrogen temperature. The use of limit sensors based on low-temperature devices will increase in the future, along with the demand for superconducting interconnects. In the course of manufacturing the interconnects, the wiring technology will be honed enough for its application ultimately to supercomputers.

5) Impact on Society and Economy

a) The technology will enable Japan to secure an economic superiority.

b) The technology will grow to be an important technology that will support the future information society.

c) The technology will further heighten the high-level knowledge and information-intensive society based on semiconductor systems that is anticipated to arrive over 10 years later. The world of superconducting electronic systems, having both features of high-level integration and superhigh-speed operation, that are superior to human brains is beyond imagination.

6) Others

The chances are considered extremely small for superconductors to be used for wiring semiconductor devices or as interconnects between chips. Even if room temperature superconductors are discovered, their use will probably be limited to a few exceptional applications such as power devices. The limits of semiconductor devices have been discussed a great deal for the past few years. However, systems incorporating semiconductor devices are a field that is expected to flourish even more. What this means is that the time-tested, existing devices will be the products of choice. Superconducting devices will not see this day for some time.

(5) High-Frequency Devices

Five persons responded to the question on the future trends of high-frequency devices.

1) Technical Forecasts and Market Scales

Table 2.2-12 gives the results of the questionnaire survey on technical forecasts and market scales.

a) Technical forecasts

• Metallic systems: Because of the constraints arising from liquid helium cooling, there are scant prospects for metallic superconducting high-frequency devices to find an increasing use in commercial applications. Their applications will be limited to special fields, such as space and astrology.

• Oxide systems: Thanks to the progress in thin film growth technology, it has become possible to downsize application systems that operate at 77 K and the prospects are bright to realize passive devices on the order of 100 GHz (filters, cavities, antennas). As for active devices, the growth of lamination technology and microprocessing technology is awaited. Passive devices alone would result in applications in limited areas. Although the rise in the cooling temperature to liquid nitrogen temperature is a big advantage, without the development of a simple refrigerating device, this alone would not generate a drastic increase in demand from the commercial sector.

b) Market scale

• Metallic systems: The demand will be only about as large as the number of radio astronomical observatories. How large a demand there will be from space and the military is impossible to forecast.

• Oxide systems: Replacements for metallic systems. When used in communications systems, the liquid nitrogen refrigeration will work as a constraint on the diffusion of the systems. Therefore, oxide systems will be used mainly in the trunk system. The current market for electronics systems, electric meters, and communications equipment totals some ¥3.6 billion. Assuming superconductors become practical, we calculate that the value of the systems and equipment that demand the use of superconducting high-frequency devices is 1~2 percent of the above figure, which translates into a market of about ¥50 billion for superconducting high-frequency devices.

c) Technical prospects

Technical development will steadily progress in the fields related to astrology, space, and the military. Metallic material devices will establish the basic configuration and oxide superconducting materials will expand the scope of applications. In oxide systems, the development of active devices is important and the realization of Josephson tunneling junction devices, in particular, is awaited. When a small refrigerator is developed, equipment incorporating superconducting devices will be used in the civil sector.

Table 2.2–12. Technical Forecasts and Market Scales (High–frequency devices)

	Calendar year → 1990 2000 2010 2020 2030
(1) Metallic superconductors	
(Technical forecasts)	
• Completion of a practical material	
• Where devices will be used	Special fields such as radio waves, astrology, and space
• Completion of a prototype	
• Completion of a test system for demonstration	Is basically completed
• Commercialization	

	Commercial-ization	Initial market	10 years later	20 years later
(Market scale)	2000–2008	¥ 1 billion	¥ 2 billion	¥ 3 billion
	1997–2003	¥ 100 million	¥ 200 million)	¥ 300 million

	Calendar year → 1990 2000 2010 2020 2030
(2) Oxide superconductors	
(Technical forecasts)	
• Completion of a practical material	
• Where devices will be used	Astrology, space, military, large-capacity communications, high-speed signal processing
• Completion of a prototype	
• Completion of a test system for demonstration	
• Commercialization	

	Commercial-ization	Initial market	10 years later	20 years later
(Market scale)	2000–2020	¥ 100 million	¥ 50 billion	–
	2004–2013	¥ 200 million	¥ 400 million	¥ 800 million

d) Where superconductors will be used in systems

Superconductors will be used to receive and amplify sections of radio waves in communications equipment and analog signal circuits.

e) Schematic specifications

When used in trunk systems, the device's size is not very important. However, the smaller, the better. Superconducting high-frequency devices have the handicap of needing a refrigerating system, so they are desired to have a performance capability that is larger by an order of magnitude than their competing technologies.

2) Major Tasks in the Future

a) Technical tasks

Thin-film growth and processing technology (on semiconductors, lamination, microlithography), junction technology, noise reduction, development of a new material that operates at about 150 K.

Solutions to technical tasks—Elucidation of superconducting materials from the principles of physics and chemistry enables their physical properties to be controlled from the manufacturing side. Another is to explicate the mechanisms of superconductivity.

b) Social and economic tasks

Because of the issue of economics, it is very difficult for ultrahigh technology to find its way into general society.

Solutions to technical tasks—Provision of assistance for research on a long-term basis; a rise in the need for superlarge-capacity and superhigh-speed devices as a result of drastic increases in communications and the amount of data that need to be processed; and radio waves in the 100 GHz-THz zone will be used in fields other than communications.

c) Peripheral technologies needed for commercialization

• Refrigeration technology (liquid nitrogen level, small size, low power consumption, insulation package technology)

Conformity with peripheral equipment, low cost, and ease of use.

There is a refrigerator with a panel-like refrigerating section (80 K), but it is far short of the target in terms of small size when the cooling equipment is included; it will take 10 to 20 years of development before the refrigerator is reduced to the size of the fan for air-cooling and becomes easy to use.

- Semiconductors and dielectrics for superconducting thin film substrates

  Development of active devices, expansion of the frequencies used, device miniaturization.

  R&D has just been started.

  Depending on how strong the needs are for superconducting high-frequency devices, the development will accelerate or decelerate. However, about 10 years will be needed.

3) Conditions Necessary for Realization

a) Needs

Pure scientific, state-level investments for radio astrology and space exploration, and increasing needs for processing of large-capacity communications and data.

b) Role of government

Investment for new technology applications, and assistance for research on a long-term basis; a new loosening of restrictions on the radio wave bandwidth for commercial use; and preferential treatment from taxation of investment for research.

c) Research funds

To spread widely the risks of undertaking an R&D project by conducting it as a national project.

d) Research structure

The development of devices should be undertaken as a national project, with the actual jobs undertaken by individual enterprises (enterprises mainly in the communications and information fields).

e) Personnel

To recruit engineers and researchers in the microwave and millimeter wave field.

f) Reliability and safety

To have levels of reliability and safety that are higher than those for existing electronic devices.

g) International cooperation and competition

International cooperation is desired in the basic research and key technology R&D. Research needs to be promoted while efforts to establish international

standards must be made simultaneously. Japan is considered to have a big role to play.

h) Scenario for realization

For realization, improvements must be made on the superconductors' already clarified various properties, and a deeper understanding of the true nature of new seeds is desired. These are the motives that underlie the foundation for realization. The first stage will be to demonstrate at the laboratory level superconductors' possibilities for use as high-frequency devices, followed by their uses as passive products in specific fields such as astrology and space. The second stage will proceed to the development of active products and their uses in high-speed communications and data processing fields. The third stage will be the maturation of superconducting integrated circuits for high frequencies, and with the completion of an ultrasmall low-cost cooling device, high-frequency devices will come to be widely used in the civil sector. Radio waves in the 100 GHz-THz zone will be used not only in the field of communications but also in other fields, such as, for example, sensors for object recognition.

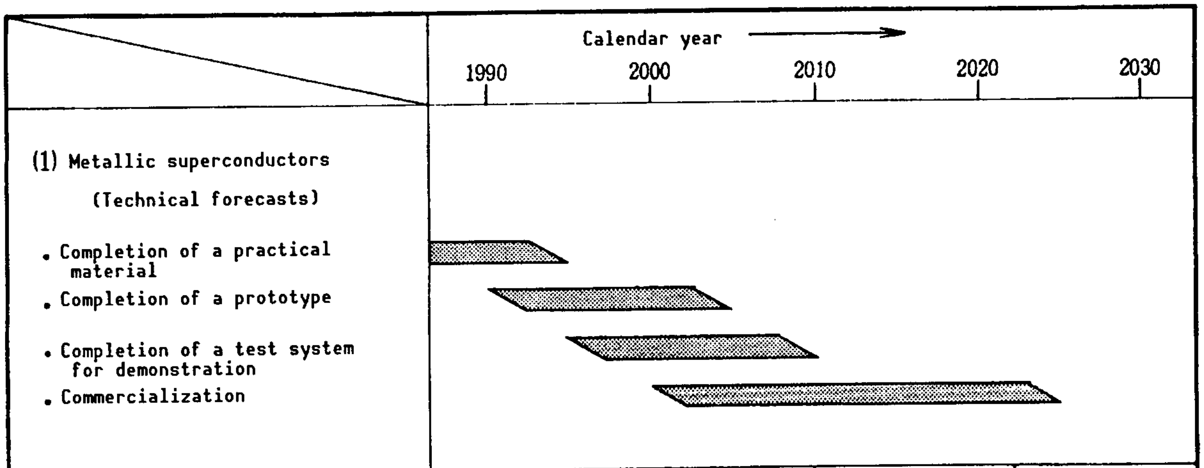
(6) New Devices

Five persons responded to the questions on the prospects for superconducting devices, on the possibilities of new devices, as well as on the possibilities of new devices employing high-temperature superconductors. Table 2.2-13 gives the future market and its scale. The following give brief descriptions of the results of the survey.

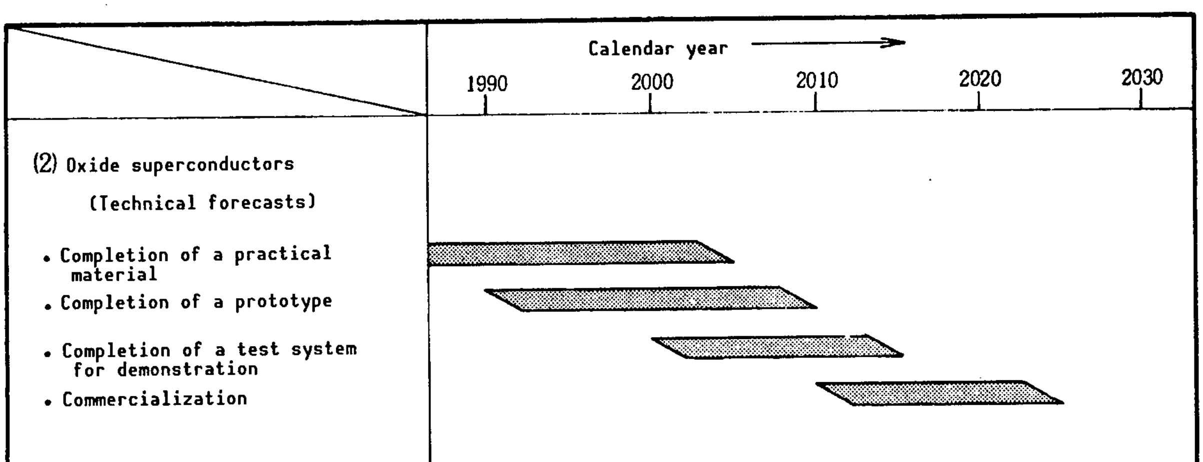
1) Future of Superconducting Devices and Possibilities of New Devices

In the category of semiconductors, development will progress rapidly toward the goals of higher speeds, smaller power consumption, and higher integration. This will be followed by trial manufacture of devices that best suit the new systems and computer architectures. Notwithstanding such a rosy picture, however, none of the respondents forecasts that superconducting devices will garner a large share of the market for electronic devices. A majority are waiting for the development of superconducting devices that are highly harmonious with semiconductor devices yet surpass semiconductors in performance characteristics, or of superconducting devices having device capabilities that are theoretically not found in semiconductor devices. As concrete examples of the former, semiconductor devices incorporating high-temperature superconductors with high superconductivity gaps as part of their elements (such as superconductor base transistors) and the three-terminal devices described previously are cited. Since superconducting three-terminal devices show operating characteristics similar to semiconductor devices, except for operating voltage, in designing systems incorporating them, the large body of knowledge on semiconductor circuit design may be used. Compared with existing Josephson devices, superconducting three-terminal devices have higher compatibility with semiconductor devices. As for the semiconductor devices, the responses were that although the potential of such devices being developed is large, none came forth with any concrete ideas.

Figure 2.2-13. Technical Forecasts and Market Scales (New Devices)



(Market scale)	Commercialization	Initial market	10 years later	20 years later
	2003–2012	¥ 10 billion	¥ 20 billion	¥ 30 billion



(Market scale)	Commercialization	Initial market	10 years later	20 years later
	2010–2030	¥ 50 billion	¥ 100 billion	¥ 200 billion
	2015–2020	¥ 10 billion	¥ 100 billion	—

The fluxoid quantum device is known as a device featuring ultralow power consumption, a feature not obtained with semiconductor devices. The ordinary Josephson devices and superconducting three-terminal devices use, as with semiconductors, fluxoid quantums as the signal carrier. Quantized magnetic fluxes exist inside the superconducting closed circuits including Josephson junctions, and in the fluxoid quantum device the fluxoid quantums are used in the signal carrier, and the device is called by various names, such as the soliton device or the phase mode device. The greatest feature of the fluxoid quantum device is that no power is consumed at all while the fluxoid quantum stays within a closed circuit, and power is consumed only when the fluxoid quantum moves on to another closed circuit. This enables the device to be operated at a fraction of the power needed to operate an ordinary Josephson device. Whether this device, exploiting its advantage of low power consumption, will prove to be the trump card for solving the heat generation associated with high-speed and high-integration devices, a problem that semiconductor devices will have to confront at some time, is still unknown. The device has its own problems: since it uses a fluxoid quantum having a small energy as the signal carrier, it is vulnerable to noise; it is questionable if high-level integration of the device can be realized free of crosstalk.

In the field of semiconductor devices, in keeping with advancing device miniaturization, research has been proceeding into quantum effects that appear in the mesoscopic region. In the field of superconducting devices, studies have been made on micro-Josephson junctions of below 1,000 Å, and from these studies has emerged an idea for the single electron (pair) tunneling device. The localized existence of electrons (pairs) in a microscopic junction increases the Coulomb interactions of electrons to a level that cannot be ignored any more, and the junction shows characteristics that differ from those of ordinary Josephson junctions. The aforementioned device has as its basic structure a combination of two microjunctions. When charges are implanted into it from the outside, the device works as a microscopic three-terminal device. Whether devices such as this that were born out of the effort for device miniaturization will become the mainstay of electronic devices in the future is unknown.

2) Possibility for Realization of New Devices Using High-Temperature Superconductors

An example of an ultrahigh-speed device, obtained by exploiting the large superconductivity gap in high-temperature superconductors and by combining such a superconductor with a semiconductor, is the superconductor base transistor. The base resistance and the running time of carriers through the base are cited as the main factors that determine the response speed of a bipolar transistor. The use of a thin superconductor base in the superconductor base transistor is expected to give it an ultrahigh-speed response. The mechanisms that cause superconductivity in high-temperature superconductors are still unknown, but the following characteristics have been clarified: the carrier density is small, the characteristics of superconductivity are sensitive to the carrier density, the average free path of carriers is short, and the coherence length is short. Many of these features work disadvantageously for the fabrication of Josephson junctions, and properties of such junction

devices, except grain boundary Josephson junctions, are not yet fully known. However, some say that these features are not necessarily disadvantages for the use of high-temperature superconductors in device applications. The two characteristics, i.e., small carrier density and the high sensitivity of superconducting characteristics to the material composition in the carrier density region, suggest that compared to existing metallic superconductors, the high-temperature superconductor may respond more easily to external stimuli such as light, external electric fields, and implantation of quasi-particles. Furthermore, when we consider a junction of a high-temperature superconductor and a conductor at room temperature, the device would have characteristics, in addition to the above two, of a short coherence length and a short average free path. Then, the state of interface remains localized in close vicinities of the interface on the high-temperature superconductor side, and this may make it possible to change the state of interface in a short time without changing the interior of the superconductor, that is, changing the bonding characteristics by applying external stimuli. Many respondents emphasized the importance of conducting research on interfaces between high-temperature superconductors and other materials to realize devices incorporating high-temperature superconductors, and expectations have also been raised for the discovery of new device principles through the elucidation of mechanisms of high-temperature superconductivity.

2.2.4 Energy Field

(1) Generators

Four persons responded to the question on the future trends of generators.

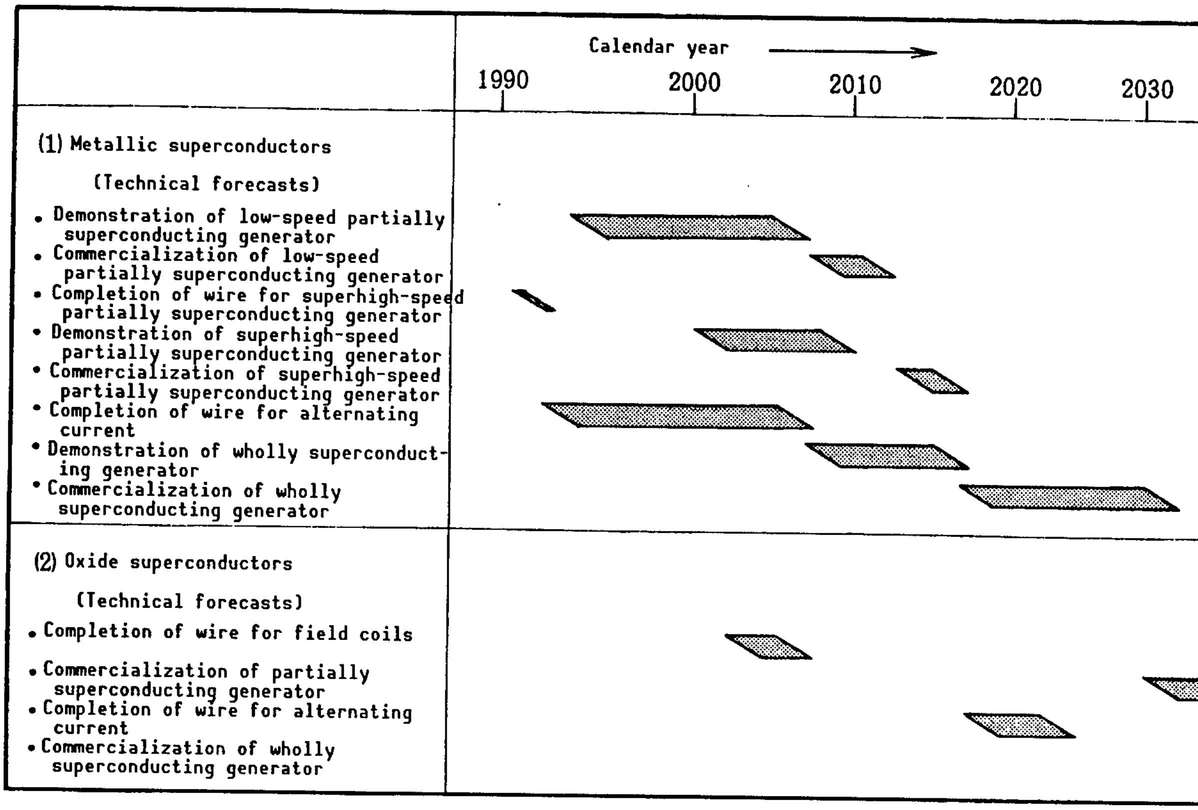
Scenario and Forecasts on Schedules

Since the development of generators is being promoted under the "Super-GM" program, it would be appropriate to consider a scenario for development in line with the program.

The first stage is the application of superconductors in low-speed versions of partially superconducting generators incorporating metallic superconductors that give little change to field current. In this case, the most promising idea is to replace the existing medium-to-small-scale generators in the consumer areas with the low-speed superconducting generators, and they are forecast to have capacities of about 200 MW in the case of combined cycle generators and about 300~600 MW in the case of ordinary thermal generators. Since these generators are installed in the middle of the system, they pose little problem associated with stability, and low-speed partially superconducting generators would do the job fully.

The next stage is to increase the stability of large-capacity power sources (600~1,100 MW) in remote areas, and a demand would arise for superhigh-speed partially superconducting generators that contribute to increased stability. A wholly superconducting generator will come after the superhigh-speed partially superconducting generator because it requires the development of a low-loss wire for alternating current.

Table 2.2-14. Technical Forecasts (Generators)



*Estimated number of units for introduction

On the other hand, the prospect of generators incorporating oxide superconductors is still far from certain. When the mode of operation of such generators—rotations in high magnetic fields, subjected to high mechanical stresses—is taken into account, the debut of even a partially superconducting generator will be in 2030 or later.

Table 2.2-14 gives forecasts of the developmental schedules and Table 2.2-15 gives the market scales.

Table 2.2-15. Market Scales (Generators)

	Market scale	
	Units/year	¥100 million/ year
(1) Metallic superconductors		
• Low-speed generator	2	10,000
• Superhigh-speed generator	3	20,000
• Wholly superconducting generator	3	25,000
(2) Oxide superconductors		
• Partially superconducting generator	3	18,000
• Wholly superconducting generator	3	23,000

(Grounds for calculations)

• The peak load of the nine electric power companies had been increasing at a rate of 2.5 percent per year (the actual records over the 1982–1986 period). If the peak load continues to increase at this rate, the amount of electricity required 2 years from now would reach 180,000 MW (1986 = 110,000 MW) and 70 units of 1,000-MW capacity generators would be needed. This translates into 3.5 units per year. Therefore, the annual demand was assumed to be about three units of generators.

• The ultrahigh-speed partially superconducting generators are assumed to be newly built machines, and their costs are estimated at 1.2 times the cost of an existing 1,000-MW generator.

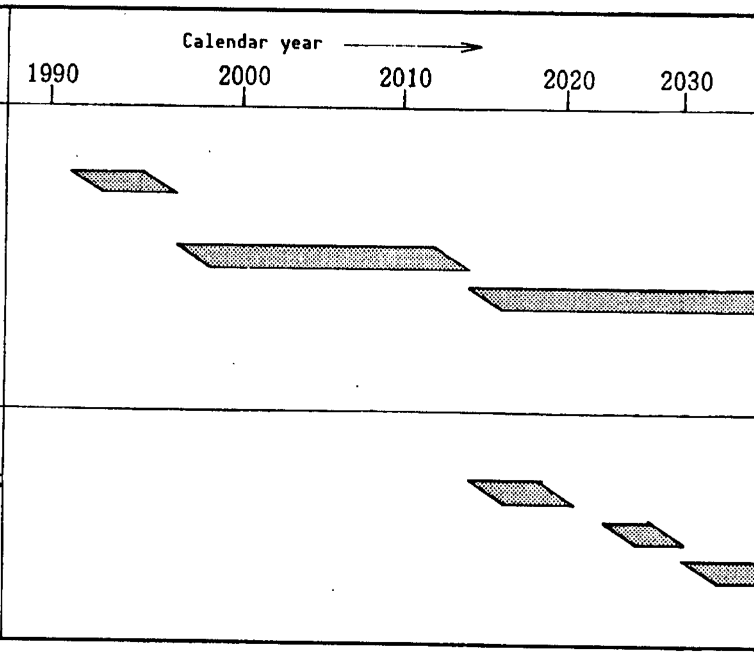
• The low-speed partially superconducting generators are assumed to be replacements, and their costs are estimated at 1.3 times the cost of an existing 300-MW generator.

• The wholly superconducting generators are estimated to cost 1.5 times the cost of a newly built version of an existing 1,000-MW generator. The multiples used in calculating the costs were based on the report on the "Super-GM."

• Costs of the generators using oxide superconductors are 0.9 times the costs of generators using metallic superconductors.

Table 2.2-16. Technical Forecasts (SMES)

	Calendar year →
(1) Metallic superconductors	
• Period when development of fundamental technologies for small-to-medium-capacity SMES will be completed	
• Period for demonstration of small-to-medium-capacity SMES	
• Period for commercialization of small-to-medium-capacity SMES	
• Period for demonstration of large-capacity SMES	
• Period for commercialization of large-capacity SMES	
(2) Oxide superconductors	
• Period for completion of wire for SMES	
• Period for completion of fundamental technology development	
• Period for demonstration	
• Period for commercialization	



(2) SMES

Four persons responded to the question on the future trends of SMES.

1) Scenario and Forecasts on Schedules

SMES are expected to find high value-added uses in such applications as the devices for increased generator stability installed in the vicinity of the generator or as the multipurpose devices (system stability, compensation for load fluctuations). Since the capacity of the coil section in SMES needed for improving the static stability is only about 20 percent of the generator electric oscillation, capacity is in the 10~100 kWh range. Capacities on the order of 10 MWh are also enough for load fluctuation compensation.

As such, coils for small-to-medium-scale SMES are expected to be developed early. However, unless permanent current switches are developed, SMES of this kind will have to use thyristors in place of permanent current switches, which gives rise to large losses. Therefore, for SMES to be used in electric power systems as a system, development of these fundamental technologies needs to be well balanced.

SMES based on oxide superconductors are hard to predict, but they will be developed in the mid-21st century (Table 2.2-16).

2) Estimated Number of Installations

Assuming the nine electric power companies install a unit at intervals of three years, a total of three SMES will be installed per year.

(3) Accelerators

Three persons responded to the question on the future trends of accelerators.

1) Technical Forecasts and Market Scales

Table 2.2-17 gives the technical forecasts and market scales of accelerators. Accelerators based on metallic superconductors have already been commercialized, but some types of accelerators are still in the developmental stage. Commercialization of accelerators based on oxide superconductors is forecast to start in 2030 or later; that is, a development period of about 40 years is needed.

The technical forecasts described here are on a large-size accelerator for high-energy physics research. When accelerators are mentioned, they generally include not only the above large-size accelerator but also small-to-medium accelerators for medical uses. Included in the latter category of accelerators are SORs and cyclotrons. The SOR is described later. Various kinds of cyclotrons for positron emitters, for heavy charged particles, such as heavy ions, π-mesons and protons, and for "linked neutrons" have been developed, and development of their superconducting versions is making headway but are outside the scope of the current survey. The beam energies of large-size accelerators for high-energy physics research have been increasing with each new project for accelerator construction and the current energy capacity is about 20 TeV. Introduction of superconductivity is becoming indispensable for large-scale accelerators to reduce the costs of constructing them and to save electricity needed to operate them. A large-size superconducting accelerator incorporating about 1,000 superconducting magnets is operating at the national Fermi Accelerator Research Laboratory (TEVATRON) in the United States. This indicates that the reliability of these magnets has been proven and that the technology supporting their high reliability, i.e., their design and manufacturing technology, has been completed. Large-scale accelerators that follow TEVATRON are anticipated to build on the U.S. technology. Remaining tasks are increases in yield and improvements in production technology.

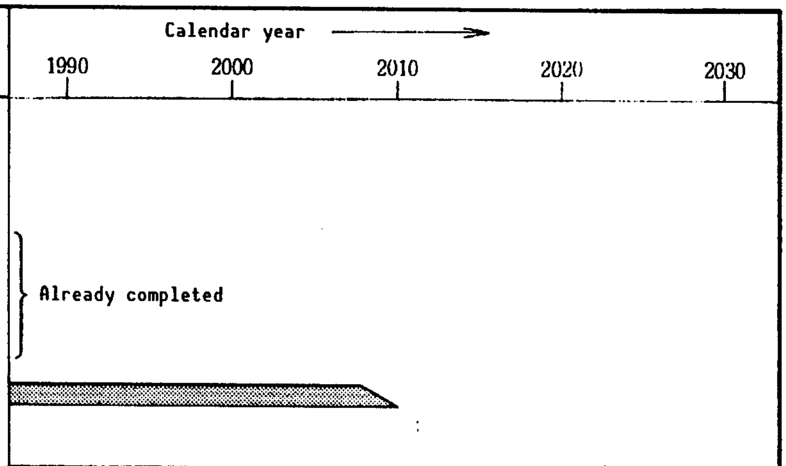
The grounds used for calculating the market scales are the following. It is assumed that large-scale accelerators will be limited to academic purposes in the near future and that the targets are the superconducting super collider (SSC) planned in the United States and the large hadron collider (LHC) a European project. These are one-at-a-time projects, and it is difficult to forecast if plans for large-scale accelerators will be drafted once the above-mentioned projects are completed. Suppose, for example, that oxide superconductors become operational in 30 years, and it is quite unknown if the demand for large-scale accelerators for academic uses will exist then.

Table 2.2-17. Technical Forecasts and Market Scales (Accelerators)

(1) Metallic superconductors

(Technical forecasts)

- Completion of a practical material
- Completion of a prototype
- Completion of a test system for demonstration
- Commercialization



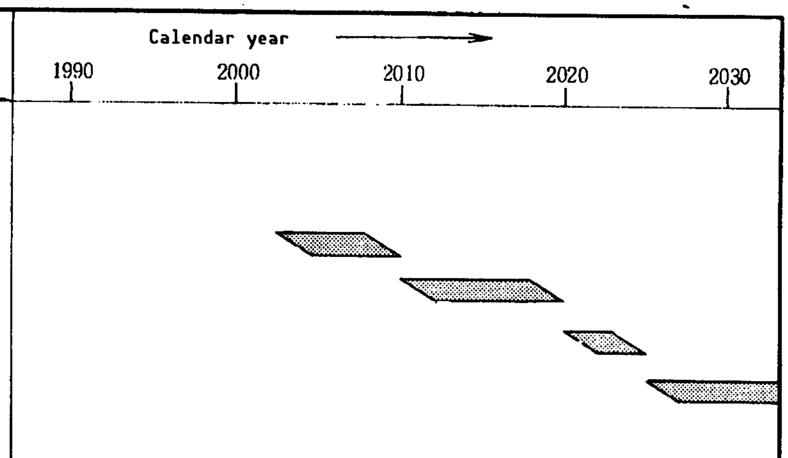
(Market scale)

Commercialization	Initial market	10 years later	20 years later
2000 – 2010	¥ 20 billion	¥ 2 billion	—
Commercialized	¥ 500 million	¥ 1 billion	¥ 2 billion

(2) Oxide superconductors

(Technical forecasts)

- Completion of a practical material
- Completion of a prototype
- Completion of a test system for demonstration
- Commercialization



(Market scale)

Commercialization	Initial market	10 years later	20 years later
2025 –	¥ 2 billion	¥ 4 billion	¥ 4 billion
2025 –	¥ 2 billion	—	—

Table 2.2-18 gives superconducting systems incorporated in superconducting accelerators for each of the market scales listed in table 2.2-17.

Table 2.2-18. Composition of Large-Scale Accelerator

Composition	Kind of magnet	Remarks
Main ring	Bipolar magnet, tetrode magnet refrigeration, liquefaction system	For market
Particle detector	Thin large solenoid magnet	Not for market
Attached facilities	Long solenoid magnet (cavities)	

Schematic specifications of the bipolar magnet for deflection that is used in the SSC are given in Table 2.2-19 and Figure 2.2-2.

Table 2.2-19. Schematic Specifications of Bipolar Magnet for SSC

Deflecting electromagnet

Central magnetic field	6.6 T
Electromagnet length	17 m
Current density (coils)	420 A/mm^2
Magnetic field uniformity (beam space)	10^{-4} Before compensation Representative value
Coil temperature	4.35 K
Number of magnets needed	7,680

2) Important Tasks in the Future

Large-scale accelerators use large numbers of magnets, ranging from about 1,000 for TEVATRON to about 10,000 for SSC, and the technology needs to be established for manufacturing high-performance technology of magnets at low cost and in high yields. The basic manufacturing technology of magnets based on metallic superconductors has been accumulated in the course of the development of TEVATRON, and the priority technical task now is to establish the manufacturing technology for volume production. In the case of magnets based on oxide superconductors, developing wire material for high critical current density is the most important technical task.

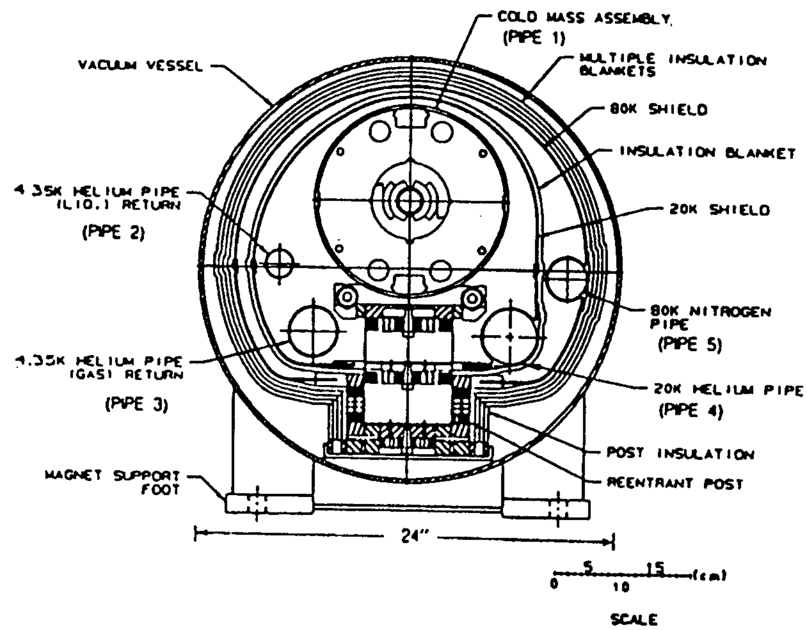


Figure 2.2-2. Schematic Specifications of Bipolar Magnet for SSC

In realizing a large-scale superconducting accelerator, an important first task is how to win a social consensus on the academic importance of exploring the true nature of matter, force, and energy using enormous amounts of energy. Technically speaking, introducing superconductivity is necessary if a large-scale accelerator in the class of SSC is to be developed. In terms of economics, no single nation would be able to shoulder the development costs all by itself, so a second task is how to win world agreement on the necessity of such a project. The achievements of the project, obtained at enormous costs of technical endeavor and financial expense, should not be used only to satisfy the academic interests but should be diverted to the cause of building a high-level industrial society, and this is a third task.

The superconducting accelerator technology has always been leading superconductor technology, and in the past a successful large-scale project has always contributed to rapid advances in other superconductivity application fields. It is, therefore, desired that the development of a large-scale accelerator provide a forum for gigantic science education, not only for peripheral technological fields including refrigeration, vacuum, control, and analysis but also for academic people and industrial engineers.

3) Conditions Necessary for Realization

The following are the conditions necessary to realize a large-scale superconducting accelerator.

a) Since a large-scale accelerator is an academic and experimental system, it is necessary to enlighten people from broad ranks of society about the

intimate relationship between the needs for basic science research and such experimental equipment and obtain a social and international consensus to construct the accelerator.

b) While not limiting its role to assisting researchers and engineers engaged in basic research, the government is required to adopt a policy of international cooperation and implement it.

c) While upholding a budgetary policy under which research funds are equitably appropriated for basic research, it is desired that the government make efforts to set up an international fund to facilitate securing of the site to construct a comprehensive system and its operation.

d) Researchers and engineers engaged in an R&D project are released as soon as the project is accomplished. Therefore, to free the research people from such fears of a furlough, it is necessary to establish an international research structure under which they will be free to find a research lab or a job of one's choice.

e) In the initial stages of superconductivity technology, it was believed that a quench accident is an inevitable accomplice to the technology, making people view the safety and reliability of the technology with doubt. On this point, it is necessary to educate people on the progress of the technology.

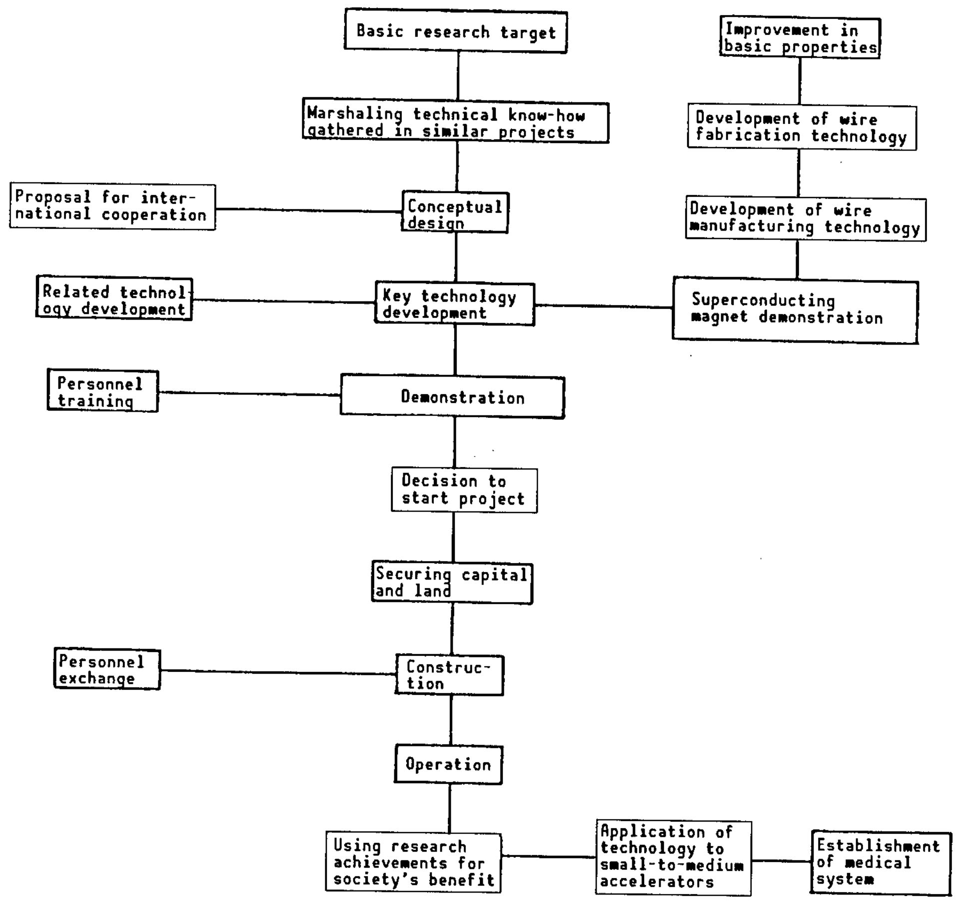
f) Even if a large-scale accelerator is to be developed under an international cooperative framework, countries participating in the effort should not be relegated to the role of sharing the burden of the technical development but should actively work to invigorate technical exchanges. To that effect, not only individual researchers and engineers but also individual countries are required to possess indigenous technologies up to the international standards.

4) Scenario for Realization

A scenario for the realization of a large-scale superconducting accelerator based on oxide superconductors is shown below.

5) Impact on Society and Economy

The completion of a large-scale accelerator is expected to affect the following: 1) a linkage to a higher hierarchy accelerator project; 2) a great advance in superconductivity-related technology; 3) pioneering of an advanced industrial society; and 4) realization of space-level education in basic science.



[Scenario for realization of a large-scale superconducting accelerator]

4. SORs

Three persons responded to the question on the future trends of SORs.

1) Technical Forecasts and Market Scales

Table 2.2-20 gives technical forecasts and market scales for SORs. SORs based on metallic superconductors have yet to be commercialized, and they are expected to appear on the market around the year 2000. SORs based on oxide superconductors, on the other hand, are expected to hit the market in 2020 or later.

The grounds for the technical forecasts are the following. SORs are also contained in the category of synchrotron radiation (SR), and among the systems generally called by the term SOR are medium-to-large-scale SRs for academic research, SRs for super LSI manufacturing and small medical diagnosis systems, and general-purpose SRs as high luminescent light sources. Consequently, included in the generic term SOR are systems in a wide range of electronic energy levels from 6 GeV to 1 GeV.

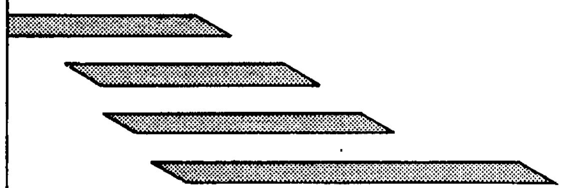
Table 2.2-20. Technical Forecasts and Market Scales (SORs)

Calendar year → 1990 | 2000 | 2010 | 2020 | 2030

(1) Metallic semiconductors

(Technical forecasts)

- Completion of a practical material
- Completion of a prototype
- Completion of a test system for demonstration
- Commercialization



(Market scale)

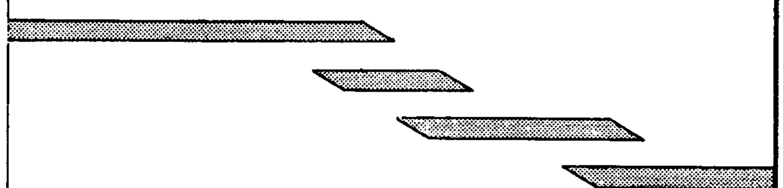
Commercial-ization	Initial market	10 years later	20 years later
2010–2020	¥ 5 billion	¥ 25 billion	¥ 250 billion
1998–2010	¥ 200 million	¥ 200 million	¥ 200 million

Calendar year → 1990 | 2000 | 2010 | 2020 | 2030

(2) Oxide superconductors

(Technical forecasts)

- Completion of a practical material
- Completion of a prototype
- Completion of a test system for demonstration
- Commercialization



(Market scale)

Commercial-ization	Initial market	10 years later	20 years later
2030–	¥ 4 billion	¥ 20 billion	¥ 200 billion
2020–2030	¥ 200 million	¥ 200 million	¥ 200 million

As for the direction of technical development, the stage is shifting from the first generation where the emitted light obtained as a by-product of large-scale deflecting magnet equipment, for high-energy physics research is exploited to the second stage where the emitted light from deflecting magnet equipment for exclusive SR use is exploited for system downsizing. The third stage, it is forecast, will shift to medium-scale, general-purpose SORs of high performance and high luminescence that will find use in a wide scope of applications. As such, the demands of society for SORs have been changing with time and the tempo with which development of superconductivity technology advances is considered to greatly affect the size of the market for SORs.

The grounds for calculating the market scales are the following: the target systems are assumed to be small- and medium-scale SORs with electron energy levels in the 1~3 GeV range. Consequently, equipment for academic research with energy levels above 6 GeV are not included. Targeted are the industrial systems of the 1 GeV class in energy level and medical systems in the 1~3 GeV class. The former class of systems are suited to X-ray lithography to manufacture semiconductor mask patterns and the latter for medical systems requiring high luminescence X-ray light sources to diagnose coronary artery disease.

As for the prospects for technical development, interest is focused on systems with an electron energy in the 1~3 GeV range. The primary reason is that systems of this scale inevitably demand the incorporation of superconductivity from the perspectives of energy savings and reductions in the operating cost. The second reason is that in exclusive SOR superconductivity wigglers and undulators are needed to raise the energy or photons, and the development of systems of 1~33 keV in photon energy requires superconducting magnets of 4~7.5 Tesla. That is, introduction of superconductivity is becoming indispensable for the development of a small-size and energy-saving type of SOR with high luminescence. The key thermal conductivity of the kinds mentioned above are being steadily accumulated for metallic superconductors, and the key technologies for oxide superconductors are also required to have as high technical standards as those for metallic superconductors as long as there are demands for them from the industrial and medical fields. In this respect, oxide superconductors for SOR systems contain too much technical unfathomableness.

The market scales are calculated based on the assumption that superconductivity will be incorporated in the systems given in Table 2.2-21 and Figure 2.2-3.

Table 2.2-21. SOR System Configuration

Composition	Remarks

Electron gun/electron linear accelerators
Synchrotron proper
    Vacuum duct
    Cavities
    Deflecting magnets, focusing magnets
Insertion light source
    Wiggler, undulator
Storaging
	Targets
	
	The synchrotron itself works as the storaging in small- and medium-scale SORs

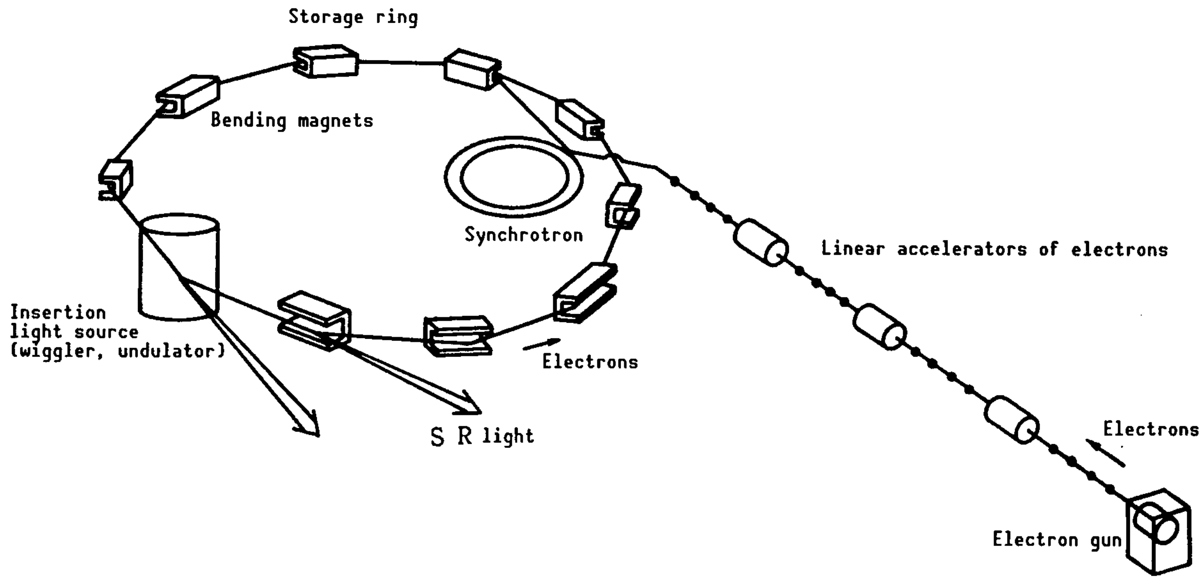


Figure 2.2-3 Configuration of SOR System

Table 2.2-22 gives schematic specifications of systems for SORs for various applications.

2) Conditions Necessary for Realization

The following comments explain the conditions that are needed if small- and medium-scale SORs are to be realized.

a) An increase in the needs depends greatly on the maturity of the semiconductor industry. In medicine, the needs will greatly depend on the social requirements for high-level diagnosis and treatment, the demand for both of which is expected to gain speed. If the social requirements to develop science and technology and new materials increase, so will the needs for medium- and large-scale SORs for academic research.

b) As for the government's role, measures need to be implemented that will accelerate the transition from a policy oriented toward large projects and large-scale equipment to a policy oriented toward installation of facilities at dispersed locations. The government will also be called upon to draft measures to guarantee that funds will be disbursed and assistance will be rendered to not only the basic fields such as sciences and education but also to actual social activities such as industry and medicine. In developing small- and medium-scale SORs, in particular, the availability of funds for private-government cooperation is an indispensable condition to establish the technology.

c) As for personnel and the research structure, establishing a personnel and research structure centered on universities and the national research labs—universities conduct basic research, while consortia of universities,

Table 2.2-22. Schematic Specifications of SORs

	Application	Specifications of SR facilities demanded (examples)	Specifications demanded from superconductivity application
Small, exclusive facilities for special uses	Super-LSI manufacturing (X-ray lithography of submicron linewidths)	•Composition: electron gun, electron linear accelerators, electron accelerator and storage rings (to use mainly emitted light from deflecting magnets) •Electron energy: ~1 GeV •Stored current: ~300 mA •Outside ring diameter: ~5 m •Photon energy: ~1 keV •Uniform irradiation of a large area	The insertion light source will probably not be used to make the system small •Specifications of deflecting magnet: Magnetic field strength: ~4 T Magnetic pole gaps: above ~4 cm
	Medical diagnosis and treatment (diagnosis of coronary arteries by DSA, etc.)	•Composition: electron gun, electron linear accelerators, electron accelerator and storage rings, wiggler •Electron energy: ~1.5 GeV (when using a 7 T wiggler) •Outside ring diameter: 10 m •Spectroscope for energy selection •Uniform irradiation of a large area •High-sensitivity and high-precision 2-D or 1-D imaging system •Image processing system	For this system to find wide use, a superconducting insertion light source is inevitably needed •Specifications of the insertion light source: Magnetic field strength: ~7 T •Specifications of deflecting magnet: Magnetic field strength: ~5 T Magnetic pole gaps: above ~4 cm
Medium-scale, general purpose facilities for various kinds of research and testing	Various academic, medical, and industrial research applications	•Composition: electron gun, electron linear accelerators, synchrotron, storage rings, wiggler, undulator •Electron energy: 1~3 GeV •Storage current: 500 mA •Outside ring diameter: -30 m •Photon energy: 1~40 keV	This system designed for multipurpose uses will require use of conductors at room temperature and a superconducting wiggler as the insertion light source. •Specifications of the insertion light source: Magnetic field strength: 4~7 T

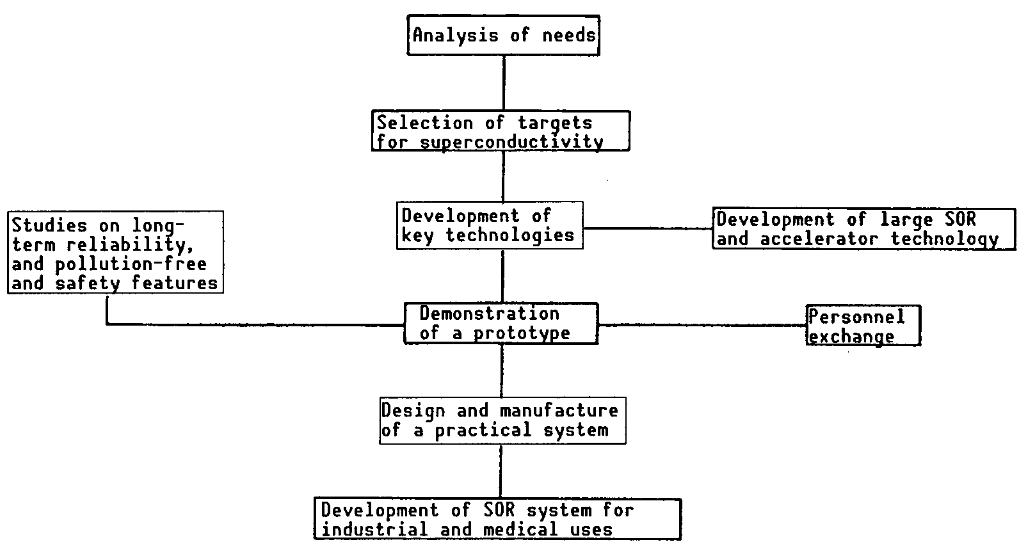
national research labs, and private industries undertake the actual development work—is indispensable for the development of small- and medium-scale SORs. In this respect, it is desired that measures will be taken that will improve the salaries of researchers at the national research labs and thereby contribute to enhanced use of talent.

d) It is said that as with accelerators, the SOR technology will see the light of day only when international technical exchange and technical cooperation is maintained. The reason is not merely economic. International technical exchange and technical cooperation are indispensable from the perspective of recruiting talented personnel and guaranteeing the livelihoods of those people engaged in the research. We should seek technical cooperation based on long-term perspectives and competition rather than resort to a closed response in the form of how to prevent outflows of personnel and technology.

e) As for the social environment, it is necessary to constantly mount a public relations campaign aimed at enlightening people about the meaning of small- and medium-scale SOR systems and to accumulate the records of their actual operations, thereby heightening the mood of the public for exploiting such systems.

3) Scenario for Realization

A scenario for the realization of small- and medium-scale SOR systems is given below.



4) **Impact on Society and Economy**

The development of small- and medium-scale superconducting SOR systems will not only meet the requirements of the highly advanced industrial and technological society but also will prove to be a tool for science and technology, supporting the progress of basic sciences. They will become one of the cores supporting the progress of superconductivity application technology.

(5) MRI

Three persons responded to the question on the future trends of MRI systems.

1) **Technical Forecasts and Market Scales**

Table 2.2-23 gives the technical forecasts and market scales of MRI systems. Superconducting MRI systems based on metallic superconductors have already been commercialized, and the market for such systems is forecast to transit at the constant rate for about 10 more years. Depending on how one looks at the associated technical tasks, the forecasts on when MRI systems incorporating oxide superconductors will be realized differ greatly. However, the general view is that such systems will be realized in 20 to 40 years.

The grounds for the technical forecasts are the following. Only the MRI of magnetic resonance (MR) technology used in the diagnosis of the human body is the target for consideration. From the perspectives of magnetic field uniformity, magnetic flux creep, and safety, metallic multicore cable is targeted as the superconducting wire material in MRI systems. As a result, not only oxide superconducting wires that have not yet been proven technologically but also superconducting wires based on compounds such as Nb_3Sn are left outside the scope of targets. However, regarding the application of oxide superconductors to MRI systems, the views are divided into two groups, one saying that those technical tasks mentioned above will be solved earlier and the other saying that those technical tasks will not likely be solved, making it all the more difficult to have technical forecasts.

The market scales were calculated on the basis of the number of hospitals and the number of X-ray CT scanners in operation and their increased rate. It was assumed that a majority of the hospitals will possess a CT scanner in five to 10 years and that thereafter the scanners at these hospitals will be replaced by advanced machines for higher-level diagnosis or those hospitals will acquire more than one such machine. However, predicting how fast the prices of MRI machines will go down with their increasing diffusion is a difficult job and the drops in prices widely vary, ranging from 20~50 percent. Thus, predicting the market value is difficult.

As for prospects for technical development, it is forecast that MRI systems targeted at protons will be used first, followed by the diffusion of MRI systems targeted at nuclides other than the proton, such as P-31, C-13, and Na-23. The diagnostic information obtained by these machines, such as spectroscopy and chemical shifts, will obtain the metabolism of the body.

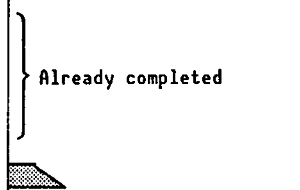
Table 2.2-23. Technical Forecasts and Market Scales (MRI)

Calendar year → 1990 | 2000 | 2010 | 2020 | 2030

(1) Metallic semiconductors

(Technical forecasts)

- Completion of a practical material
- Completion of a prototype
- Completion of a test system for demonstration
- Commercialization



(Market scale)

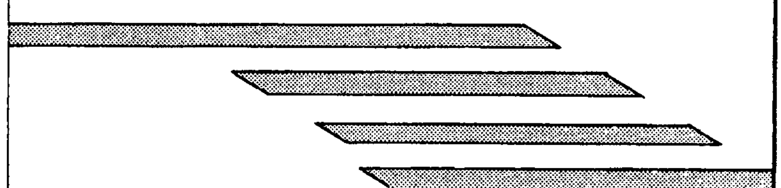
Commercial-ization	Initial market	10 years later	20 years later
Commercialized	¥ 70 billion	¥ 225 billion	¥ 275 billion
Commercialized	¥ 100 million	¥ 5 billion	¥ 5 billion

Calendar year → 1990 | 2000 | 2010 | 2020 | 2030

(2) Oxide superconductors

(Technical forecasts)

- Completion of a practical material
- Completion of a prototype
- Completion of a test system for demonstration
- Commercialization



(Market scale)

Commercial-ization	Initial market	10 years later	20 years later
2020–	¥ 2 billion	¥ 55 billion	—
2010–2030	¥ 5 billion	¥ 5 billion	¥ 5 billion

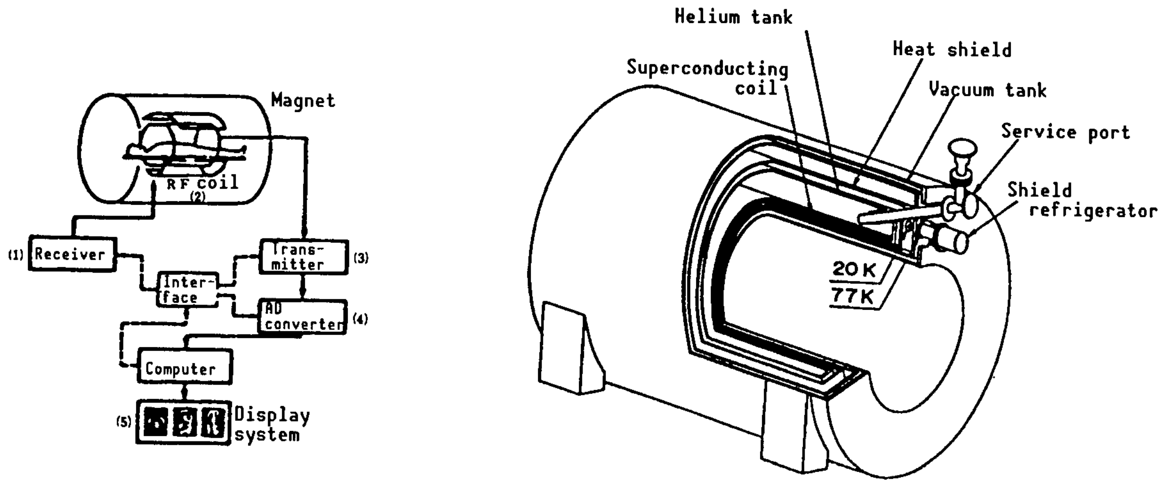


Figure 2.2-4. Configuration of MRI System

The technology is a direct extension of the nuclear magnetic resonance (NMR) spectrometer technology in high magnetic fields that is already finding practical use. As the kind of information being demanded increases in sophistication, advances in both the magnet technology for static magnetic field generation in MRI and the image processing technology will be called for in terms of both hardware and software. Especially, advances in the introduction of superconductivity in inclined magnetic field coils, high-frequency coils, and magnetic shields are awaited.

In calculating the market scales, the MRI system was assumed to contain the superconducting components given in Table 2.2-24 and Figure 2.2-4.

Table 2.2-24. Construction of MRI System

Components	Remarks
Static magnetic field superconducting magnet	Targets
Power source for the above (including shim coil)	Targets
High-frequency coil	Targets
Inclined magnetic field coil	Targets
Control cabinet	Not targeted
Image processing console	Not targeted
Magnetic shield chamber	Not targeted

Schematic specifications of the MRI are given in Table 2.2-25.

Table 2.2-25. Schematic Specifications of MRI

1) Room-temperature bore (magnets)	
For forward movement of the human body:	1 m
For animals—hands and legs:	0.1~0.6 m
2) Magnetic field strength	
Photon imaging:	0.1~1 T
Chemical shifts and imaging of other nuclides:	1.5 T
(for basic medicine):	2~10 T
3) Uniformity of magnetic field	
Imaging:	10~20 ppm
Chemical shift:	below 1 ppm
4) Liquid He consumption:	below 0.1~0.3 ℓ/h
5) Magnetic field stability:	below 0.1 ppm
6) Wet magnetic field:	below 5 G (about 40 m in domain)
7) Size and weight:	Small, lightweight (8~30 tons*)

* To include magnetic shields

2) Major Tasks in the Future

The following are the major technical tasks before superconducting MRI systems will be realized. Superconducting MRI systems based on metallic superconductors have already been commercialized and there are no major tasks for now, but developing key technologies is needed to cope with the increasing sophistication in the properties of needs. Superconducting MRIs based on oxide superconductors, on the other hand, have many technical tasks as shown below.

- Manufacturing technology of long size and high-quality wire.

- Development of interconnection and permanent current joint technology.

- Improvements on coiling methods, dimensional accuracy, and uniformity of the magnetic field in coils.

- Selection of the operating temperature after taking into account the performance, reliability, and cost.

The following have been proposed as the social and economic tasks if MRI systems are to be put to practical use.

• Self-examination as a country introducing the top-of-the-line medical technology (medical administration).

• A review of and an improvement on the point system in the Ministry of Health and Welfare's health insurance system.

Calculations have been put forth that the break-even point for an MRI system costing ¥200 million would be more than 15 patients per day, and hence introduction of MRI systems into small hospitals would be impossible unless the point system in the health insurance system is amended. Therefore, what constitutes a proper balance between MRI diagnosis technology and treatment-of-a-lesion technology in the whole medical system will have to be discussed, and a consensus on that point will have to be obtained.

The needs for the development of the following peripheral technologies have been cited.

• **Magnetic shield**

Active shield technology to shield the coils themselves to simplify the magnetic shield chamber and build at low costs is needed.

• **Low-cost computer**

As more than one MRI system is introduced, the development of systems with access to a supercomputer will be demanded. Such a system may be developed in three to five years.

• **Development of high-strength structural material**

MRI systems are going the way of higher magnetic fields, with the limits that such high magnetic fields will not adversely affect the human body. Nonmagnetic high-strength structural material will be needed for structural materials.

3) Conditions Necessary for Realization

The conditions needed for the realization of MRI systems—for their growth into versions with higher performance capabilities and higher magnetic fields —are the following.

a) In terms of needs, MRI systems are required to have higher magnetic fields to give them capabilities to diagnose not only protons but also P, C, and Na as well as to elevate their diagnosis accuracy (S/N ratio). To accumulate data on the living body by scanning animals by NMR spectrometers as well as to do magnetic resonance imaging of the human body, hardware of 20~30 T is demanded.

b) The role of the government is to establish a system that enables the influence of magnetic fields on living bodies to be systematically researched and monitored, and to make a review of its policies on biological science and research from an overall viewpoint.

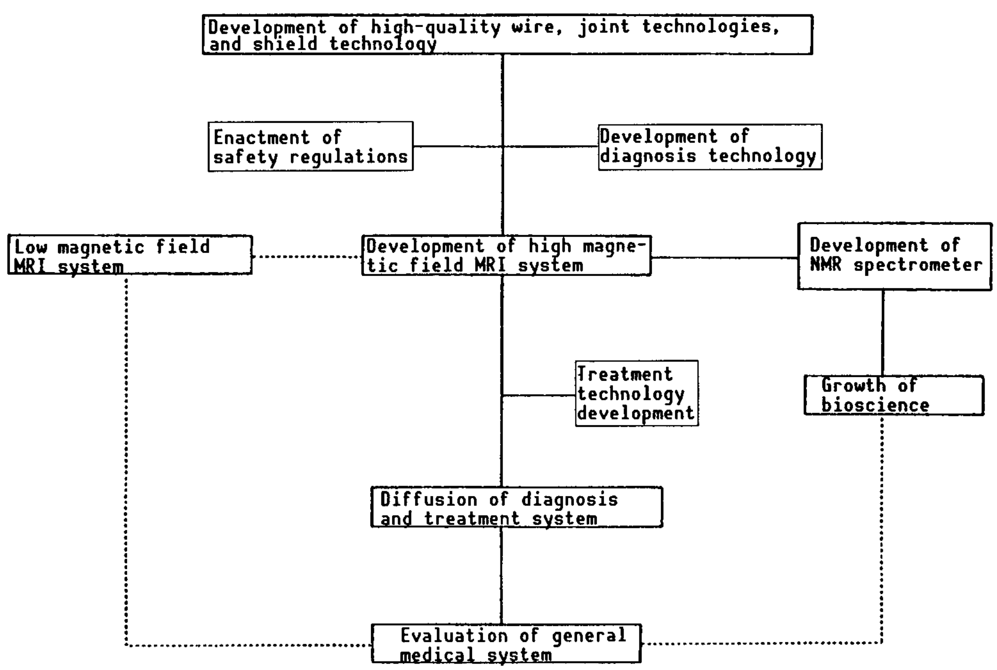
c) To train and recruit researchers and engineers who can meet these needs and technology, it is desired that a research organization be established as a forum to promote a national project, to be undertaken with the cooperation of universities, government, and industry, ideally.

d) Among the technologies competing with superconducting MRI technology are those of MRI equipment based on room temperature conductors and permanent magnet systems. These technologies will be competing with each other on the merits of their respective features for some time, but selecting technology consideration must be made on the conformity of the technology with future medical systems. A method to encourage technological competition is cooperation through invigorated international research cooperation.

e) As for the social environment, it is necessary to clarify what intensities of magnetic fields from MRI will have what effects on the human body. This is not an issue on the level of comparing the safety of exposure to MRI with the safety of exposure to conventional X-rays, but its solution should be sought as a problem common to all superconducting equipment, that is, the effect of strong magnetic fields on the human body.

4) Scenario for Realization

A scenario for the practical use of MRI systems based on oxide superconductors is given below.



5) Impact on Society and Economy

MRI systems based on metallic superconductors have already been commercialized and they have made a great impact. The realization of even pure advanced MRI systems based on oxide superconductors will enable a comprehensive diagnosis and treatment system to be established, thereby making the early discovery and complete treatment of a lesion possible. Furthermore, the ripple effects of these technologies will make it possible to scientifically elucidate the biological reactions and the reactions of brains in humans, and these findings, with the help of biotechnology, will have a great impact on the food problem. They will also work as a motive for further advancing the electronics technology developed along with the diagnosis and treatment system.

Chapter 3. Trends of Research and Development

3.1 Corporate Views of R&D

One may say that the past one or two years was a period during which superconductivity evolved from a boom period and entered into a full-fledged research era. As is apparent from the technical forecasts of superconducting materials described in the preceding chapters, the technology contains many technical tasks, the prospects for the solution of which are scarcely bright. Even in the electronics field where high J_c was obtained with thin films at relatively early stages of research, thereby giving rise to an expectation that superconductivity would be employed in the near future, technologies needed to fabricate oxide superconducting materials into devices are a long way from being established. In some fields of applications, the critical temperature demanded is much higher than that of Ti, and the superconductivity research, including the probe for new materials, is considered to be long-term research. Recent research efforts have unveiled some promising materials which, even in their bulk form, give a bright prospect for an improved J_c. In the energy field, the field considered the prime candidate for the application of such materials, the research on oxide superconducting materials is considered to be as long-term a research theme as it is in the electronics field. Such long-term research involves large investment risks, and therefore, the government is expected to assist such research projects one way or another.

With a focus on the social environment and the necessary policy measures that must be in place if development of superconducting materials is to be promoted, especially the role of the government and the requests for government help, this chapter puts together the results of responses obtained in the questionnaire. We selected 22 experts, researchers engaged in superconductivity research mainly in private enterprises, universities, and national and public research laboratories, as the targets of the current survey and obtained responses on the desirable form of research and development of superconducting materials in the future from 17 of them (77 percent of the total). The following are outlines of the survey.

3.1.1 Fields and Targets of Research Difficult for the Private Sector (Industries) To Undertake on Its Own

Answers were obtained on a broad range of research items from basic to application research. The answers are broadly divided into the four categories of 1) theory research and research for basic evaluation of physical properties; 2) research on the probe for new materials; 3) basic research on process; and 4) application research. Among the reasons why the aforementioned four fields were cited as the targets for research are the following: In fields 1) and 2), research that is not considered appropriate for enterprises to undertake alone, the following reasons were raised: "There does not exist a direct cause and effect relationship between basic theory research and productive activity"; "Development of a new material involves a big investment risk, and there aggressive research activity is hardly to be hoped"; and "A large amount of capital and a large staff are needed to install and operate large-scale evaluation equipment and analysis equipment."

Fields 3) and 4), it is believed, were proposed as joint research projects under the government's coordination. Among the reasons cited were, "Besides the fact that the basic research of a process needs to be conducted over a relatively long time, it is uncertain when the research result will be funneled into the private sector in the form of feedback, and worse, it needs a lot of research money"; and "It is desirable that systematization of superconductivity technology be undertaken as national projects as in the past." In the following, the research items with an asterisk (*) were proposed by several respondents.

(1) Theory Research and Research for Basic Evaluation of Physical Properties

1) Elucidation of high-temperature superconductivity mechanisms.*

2) Evaluation of physical properties (diffraction of a neutron beam,* evaluation of physical properties under ultrastrong magnetic fields or ultrahigh pressures,* long-term tests, and standardization of various measurement and evaluation methods).

3) Basic research to improve the critical conditions such as J_c, H_{c_2}, T_c (crystal structure, physical properties, fine structure).

4) Basic properties of oxide superconductors with a layered structure.

(2) Research and Probe for New Materials

1) Probe for new high-temperature superconducting materials.*

2) Probe for the kind of superconducting materials that are more suited to practical use.

(3) Basic Research on Process

1) Control of crystal grain boundaries and fabrication of long wire.*

2) Compounding of wire materials.

3) Introduction of pinning centers and their fixation.*

4) Lamination of thin films.

(4) Application Research

1) Development of Josephson junction devices for analog applications.

2) Basic research on ac superconductivity (development of new materials and new wire materials for use in the gigahertz zone of direct current, and development of measuring instruments incorporating such materials and of the measuring methods).

3) Systematic basic research on the support and stabilization of electromagnetic force.

4) Energy storage system.

3.1.2 Anticipated Superconductivity-Related Projects (Requests for and roles of the government)

Research projects on superconductivity and related technologies that are desired to be undertaken as joint projects (enterprises-enterprises, enterprises-universities, enterprises-national and public research laboratories, and enterprises-universities-national and public research laboratories) or national projects are listed in Table 3.1-1, according to the scales of research funds that will be needed. Broadly speaking, the research themes are divided into the following: 1) software (theory, database, funds for exchange, etc.) research and development; 2) basic research for the establishment of key technology; 3) commercialization research; 4) establishment of a research facility open to all the participants; and 5) systemization of large-scale facilities. Projects contained in categories 1) and 2) are forecast to cost no more than several hundred million yen, while projects in 3), 4), and 5) are considered to require funding of more than several billion yen.

Furthermore, for the joint projects to progress smoothly it will be necessary to establish a research infrastructure so that the enterprises, universities, and national and public research laboratories will be able to display their originality to the highest degree. At the same time it will be necessary to make sure that increased coordination between various ongoing projects is maintained. Furthermore, as to the merits of enterprises participating in a joint research project, such valuable opinions were obtained: "It will enable the company to have a medium-and a long-term perspective of when the research will be realized as a commercial product"; and "The research results will have wide application in other fields."

3.1.3 Projects Requiring Early Research and Development

Of the research items described in Table 3.1-1, the following are considered to be the R&D themes which need to be initiated at the earliest date. Several responses were also obtained that emphasized the need for the continuation and promotion, on a long-term basis, of the ongoing research projects.

(1) Basic research on improving the J_c of bulk material (correlations among pinning phenomena, microstructure, and crystal structure)

"The improvement on J_c is beginning to reach a stagnation, and this is because basic research is well done."

(2) Development of wire with high J_c at 4.2 K

"If too great an emphasis is placed on the success of a project, the result may end up as a small success."

Table 3.1-1. Assumed Superconductivity-Related Research Projects by Budget Scale (Based on survey results)

Below ¥100 million	•Elucidation of the mechanisms of superconductivity •Collection of data for standardizing the superconductivity evaluation technology •Accumulation of thermodynamic data on oxide superconductors •Compilation of a database •Establishment of the testing methods of superconducting materials and wires and their standardization •Growth mechanisms of superconducting single crystals and their thin films •Connection with current terminals •Environmental assessment of electromagnetic waves •Fund for information exchange
Above ¥100 million but below ¥1 billion	•Studies on high-purity raw materials and on their secondary processing •Introduction of pinning center •Realization of control of superconducting crystal grain boundaries and fabrication of long wires simultaneously •Development of substrate material for growing superconducting thin film •Basic research on superconducting electronics •Joint-use system for measuring superconducting characteristics •Development of a database •Basic research on introducing superconductivity into ac electric systems (limiters, substations, reactors for electric generation) •Development of an electric car mounted with small-size SMES •Development of compound superconductors based on metals for use in ac systems •Elucidation of the effect of magnetic fields and toxic and harmful substances on animals
Above ¥1 billion but below ¥10 billion	•Compounding of superconducting wire materials •Technology for fabricating low-temperature process super-conducting single crystal thin films and their junctions •Lamination of superconducting thin films •Development of specific purpose devices •Realization of tunneling junctions based on high-temperature superconducting materials •Joint research for fabrication of common high-quality samples and for the evaluation of their properties •Development of technology for evaluating superconducting properties •Synthesis of superconducting materials under critical conditions •Basic research on a dual-use cable for transmission of communications as well as direct current [continued]

[Continuation of Table 3.1-1]

[continued] Above ¥1 billion but below ¥10 billion	•Superconducting millimeter wave system •Basic research on development of ultrahigh-speed logic circuits (using Josephson junctions and three-terminal devices) •High-temperature superconducting SQUID systems •Development of an ultrasmall refrigerator •Development of SOR equipment •Elementary particle detector •Development of a prototypical small-size superconducting accelerator (below 3 GeV for electrons, and about 200 MeV for protons) •Development of superconducting equipment for factories •Development of a prototypical generator •Basic research for development of ultrahigh-speed trains
Above ¥10 billion	•Joint-use facilities for superconductivity experiments (open for use by all research institutes) •Development of material with high J_c •A large-capacity satellite communications system (using superconducting devices (~100 GHz class)) •A large-scale project for LSI •Superconducting computer systems •Proving the superiority of the Josephson junction computer (to include the Nb type of computer after a prototype has been developed) •Development of a high-temperature superconducting generator •MHD power generation •SMES systems •A prototypical superconducting linear accelerator urban SMES •Linear motor cars •Development of a superconductor-applied propulsion system (uses in ships, railway cars, and autos) •An electromagnetic catapult system •Superconducting nuclear fusion test equipment •Development of a whole superconducting generator (to include metallic low-temperature superconductors)

(3) Control of crystal grain boundaries and fabrication of long wires (by a melt method)

"Samples manufactured by a melt method (melting powdering melting growth (MPMG), quench and melt growth (QMG), or MTG) boast the highest critical current densities of all bulk materials and are drawing worldwide attention. The biggest problem in realizing their practical application is how to pull them into long wires, and if this becomes possible, a great stride will have been made toward their practical use."

(4) Improvements on the technology of fabricating bulk material into wires and on the mechanical features of such wires.

(5) Development of systems incorporating Josephson junction devices based on Nb.

(6) Development of substrate materials and of manufacturing technology of junctions (including tunneling junctions)

"Manufacture of Josephson junctions is an indispensable technology if (superconducting materials) are to find application as electronic devices but the technology has yet to be developed"; "The technology will have a large feedback effect to elucidate the properties of the materials themselves, a requirement if they are to find use in the field of electronics."

(7) High-frequency devices-related research

"The use of high-temperature superconductors is considered to be the nearest-term possibility, but the numbers of research organizations and researchers in Japan are fewer than in other countries."

(8) Development of a superconducting limiter or a unique substitute for it

"One of the causes contributing to not-so-bright prospects for the use of superconductors in alternating current systems is that to cope with unexpected short circuiting troubles designs of such systems need to be provided with unnecessary and excessive performance characteristics, which raise their costs."

(9) Establishment of a method to test high-temperature superconductive properties

"To tell the truth, we are at a technical level where we are even unable to tell how reliable the data provided by other research organizations or researchers are."

(10) Basic research for application of high-temperature superconductors (stability, characteristics at 4.2~20 K, sheath material, mechanical strength supporting material, compounding technology)

"The efforts have only been directed toward improving J_c, and the development of superconductivity technology in its other aspects is lagging behind."

(11) Manufacturing single crystals and thin films, and supplying them to various research institutes

"To evaluate properties of oxide superconducting materials, their samples of high quality are needed, and manufacturing large numbers of such samples and offering them for use by research institutes will be highly beneficial."

(12) Storage of energy, and small- and medium-scale SMES

"Improvements in energy efficiency are needed to protect the environment from destruction by the additional construction of power plants"; "Technical development is needed before the next-generation energy crisis falls on us."

(13) Preparation of a database

"A database needs to be established to avoid redundancy in future research efforts and promote projects efficiently."

(14) Effects of magnetic fields on humans and animals

(15) Effects of toxic substances on animals, and regulating their safety.

3.1.4 Facilities Desired To Be Built in Public Institutes

Of various facilities and equipment indispensable for superconductivity research, the following were pointed out as the facilities and equipment (to include their expansions) that the respondents desire to be installed at public institutions. The items marked with an asterisk (*) are those cited as needed by more than one respondent.

(1) Superhigh, superhigh magnetic field facilities (*)

(2) Neutron radiation sources (*)

(3) SORs (*)

(4) Load simulators (to include testing of the capacity to withstand the environment (*)

(5) Equipment to test flow of large currents (*)

(6) Large-capacity ac-dc converters (*)

(7) Equipment to test broad-frequency band characteristics (*)

(8) Systems for measuring material properties (full-fledged systems)

(9) Standard labs for testing wire properties

(10) Labs for testing fatigue properties

(11) High magnetic field and high electromagnetic field labs (long-term observation and measurement of their effects on animals)

(12) Ultrahigh sensitivity magnetic shields, facilities for measuring noise

(13) Integrated structural analysis equipment (neutron analysis, scanning electron microscope (SEM), transmission electron microscope (TEM), and others)

(14) Large-scale furnaces with the capability to control temperature gradients (facilities for fabricating long wires)

3.1.5 Management of Public or Semipublic Centers or Research Labs

Opinions were obtained on the desirable directions of the activities of the public or semipublic centers or research labs from the respondents. These opinions can be summarized as follows:

(1) The research equipment such as the evaluation instruments should be made available to the outsiders.

(2) The research results should promptly be made known to the public.

(3) Joint research among public research institutes, private institutes, and universities should be promoted.

(4) The public and semipublic research institutes should play a role as the centers of information on superconductivity technology for not only Japan but also the world. They are also desired to play a role as a sort of common database and as a supplement to what is lacking in academic activities.

(5) these institutes are desired to conduct tests to confirm the reliability of information on new superconductors.

(6) Not limiting themselves to research on high-temperature superconductivity, they are desired to conduct research in a broad superconductivity field (including metallic superconductors), including basic research on superconductivity and on superconductivity engineering, and to help the private research efforts in those fields.

(7) They are desired to promote research cooperation with overseas research institutes.

(8) They should promote research centered on the development of seeds for superconductors with high J_c.

(9) They should train promising young researchers as the core of superconductivity researchers in the future.

3.1.6 Conclusion

We sought the opinions of researchers engaged in the research and development of superconductivity at corporations, universities, and national research institutes regarding the directions of research and development of superconductivity in the future, and active responses were obtained calling for increased research and development of the technology. The feverish superconductivity boom has subsided a little recently, but the development of practical superconducting materials has been promoted steadily. As for the field of application of superconductivity, great expectations have been placed on electronics since it is hoped that superconducting thin films will be

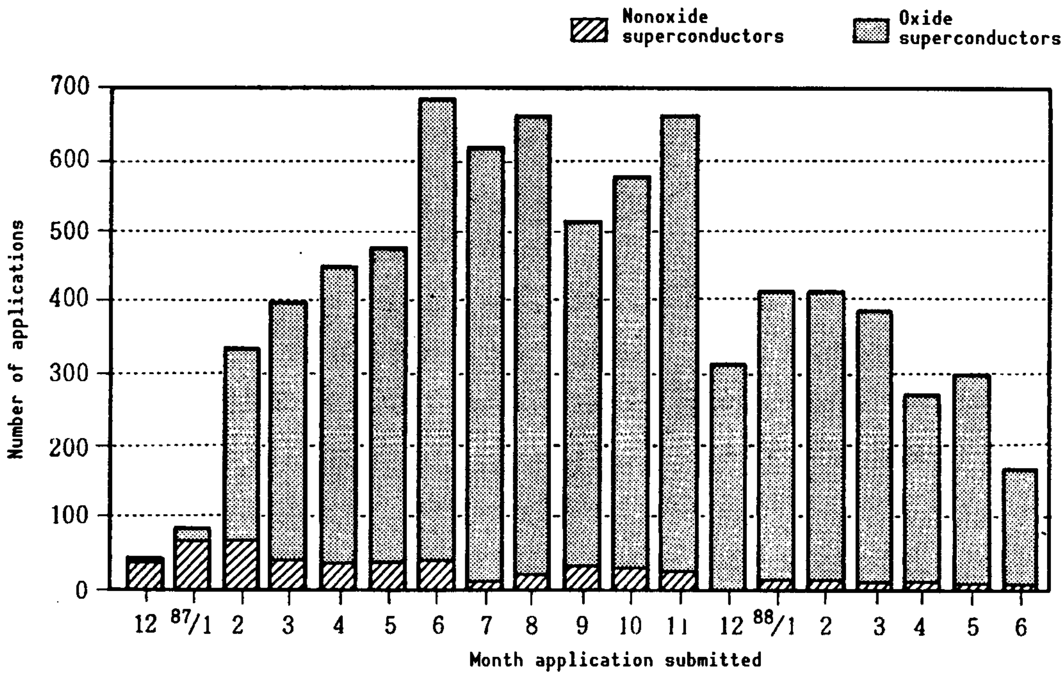


Figure 3.2-1. Applications for Superconductivity-Related Patents

realized earlier. But, due to the recent results of basic research showing that high J_c can be obtained in bulk material, expectations have been mounting for the application of superconductivity in the fields of energy, and this is an encouraging sign for the future of superconductivity research. To realize practical uses of superconductivity in large-scale equipment, the respondents have strongly called for the government to provide some form of financial assistance and to play a role as coordinator. The opinions calling for efficient promotion of research and development in the future are noteworthy in that they show a great expectation for increased research and development of the evaluation technology of superconductivity and of key technologies for superconductivity application, the very technologies that are being accumulated on metallic superconductors. We hope the results of this survey will work as a guide in drafting superconductivity research programs in the future.

3.2 Trends of Applications for Patents on Superconductors

Since late 1986 when the oxide superconductor was discovered and the first application for patents was filed, about 7,400 applications for patents on superconductors have been submitted to the Patent Office of Japan as of June 1988. The number, of course, is the largest of any country in the world, showing the rapid progress of superconductivity research in Japan.

Figure 3.2-1 gives the monthly number of applications for patents on superconductors. The graph distinguishes applications for patents on oxide superconductors from those on nonoxide superconductors. Although the number of applications on nonoxide superconductors was larger than those on oxide superconductors in the first two months, thereafter applications on oxide

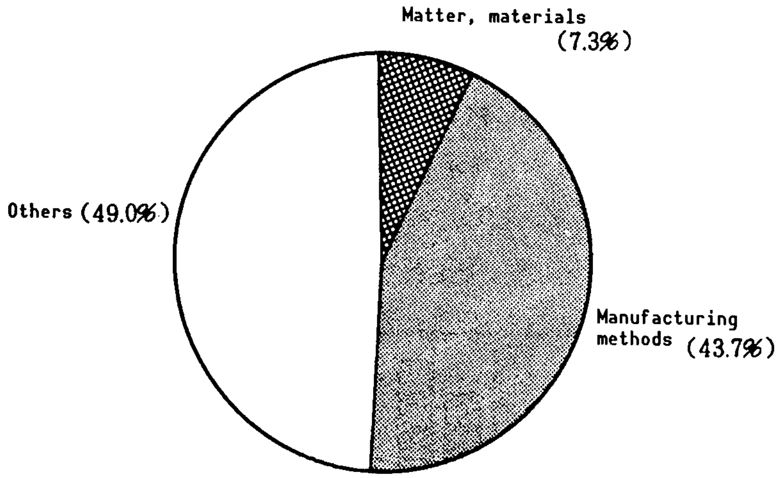


Figure 3.2-2. Patent Applications in Oxide Superconductors

superconductors were overwhelmingly larger. In the graph the peaks in applications are seen in June through November 1987.

With the beginning of 1988, applications began to slowly diminish, but the figure of July 1988 is expected to climb a bit since there are believed to be some applications still unknown to the public. The downward trend, however, is considered to continue. It is assumed that the number of monthly applications for patents will ultimately be in the 150 to 200 range.

A majority of the vast number of applications are still in the stage of mere applications, with no request for their screening as to whether they contain conditions necessary for a patent. It is anticipated that the eventual number of such requests for screening will be way below average. The reason is that since the enterprises vied with one another in submitting applications for patents, many of those applications are believed to be fundamentally similar or can hardly be put to practical use.

Patent applications in oxide superconductors can be broadly divided into three categories from their contents. The first category is those pertaining to matter and materials, the second is on manufacturing methods among which are contained the manufacturing methods of films and wires, and the third is on applications and others, including devices, MRI machines, magnetically levitated trains, etc. The ratios of applications in each of the categories to the total applications are given in Figure 3.2-2. Applications for patents on matter and materials account for 7.3 percent, those on manufacturing methods (including those of films and wires) 43.7 percent, and applications and others 49 percent.

In Figure 3.2-3 patent applications in oxide superconductors in each of the above three categories are depicted on a monthly basis. The graph shows that applications for patents on materials are the least of the three, their relative numbers in earlier months were very large. Conversely, although the number of related applications for application-patents was small in the

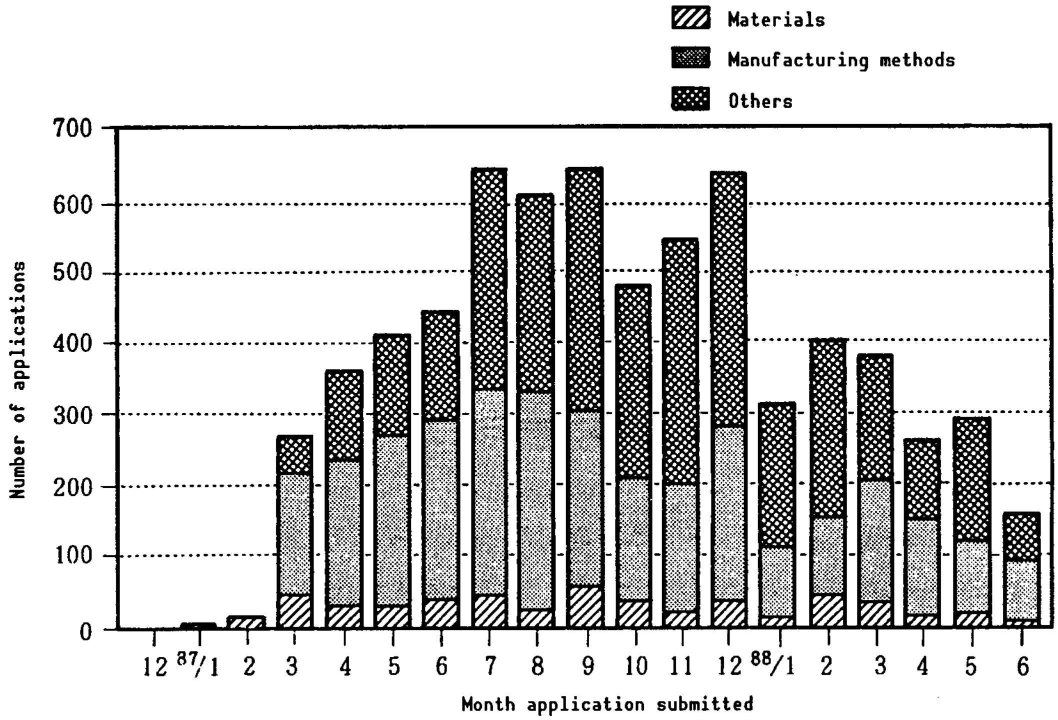


Figure 3.2-3. Patent Applications in Oxide Superconductors

earlier months, the number was largest when the total number of applications reached peaks. The graph does not follow a gently sloping curve but seems to have two peaks. The drops in October 1987 and neighboring months may have been caused by the Patent Office's public relations campaign to abstain from submitting applications as much as possible.

3.2.1 Superconducting Materials

As of June 1988, about 500 patent applications on superconductive materials had been filed. The number is exceptionally large given the fact that matter-related patent applications are extremely slow to materialize. The targets for patent applications are broadly divided into the lanthanum-, yttrium-, bismuth-, and thallium-based superconductors, but a majority are applications for patents on yttrium-based superconducting materials. Some of the patent applications are introduced below. The numbers in parentheses are the patent numbers published in the PATENT GAZETTE. When desiring to have information on a patent, one needs to submit an inquiry for the patent by identifying its number as such as one can obtain an open official report on it.

(1) Layered perovskite crystal structure: A ceramic superconductor based on lanthanum, barium, copper, and oxygen, it has a structure of $(La_{0.925}\ Ba_{0.075})_2\ CuO_4$, and a zero electrical resistance of 25 K (63-176353).

(2) Ceramic superconductor, composition: RE: rare-earth elements (such as lanthanum), AE: alkaline earth elements (Sr, Ca, Ba, etc.), TM: transition metals (copper, etc.), $x \leq 0.3$ $y \leq 0.5$ (63-190713).

(3) Oxide superconductor of a K_2NiF_4 crystal structure. Chemical formula: $(A_xB_{1-x})_2\ CO_{4(1-y)}$ ($0 \leq x < 1$, $y \geq 0$, A: Ca, Sr, Ba, Zn, Cd, B: Sc, Y, La, Ce, Gd, Yb, Lu, C: Ag, Au) (63-190713).

(4) General formula, $Y_xBa_yCuO_z$: $x = 0.2\sim0.5$, $y = 0.2\sim0.5$, $z = 1 + y + (3/2)x$. A perovskite crystal structure of a face-centered cubic crystal with a grating constant of $a = b = c$, and an axial angle of 90 degrees. It shows superconductivity at temperatures above the boiling temperature of liquid nitrogen (63-225330).

(5) Yttrium-based oxide superconductor. A perovskite oxide belonging to the tetragonal system with oxygen defects, $A_2B_4Cu_6O_{14+y}$: ($0 < y < 2.5$), A or Y, La, Yb, Lu, Sc, Al, B, B or Ba, Sr, Ca (63-225531).

(6) Yttrium-based superconductors. A majority have a composition expressed by the general formula, $R_{2-x}M_{1+x}Cu_2O_{7-y}$: R = Y, Sc, M = Ba, Sr, Ca, $0 \leq x < 2$, $0 \leq y \leq 1$, and they have a layered oxygen-defect multiple perovskite crystal structure. Transition to superconductivity begins at 94 K, a temperature above the boiling point of liquid nitrogen, and these superconductors lose resistance at 88 K (63-225572).

(7) A compound of barium, yttrium, and copper ($Ba_4Y_2Cu_7O_{14}$) is obtained by mixing copper oxide, yttrium oxide, and barium carbonate to a specified ratio and heating the mixture at 800~850°C in air (63-230521).

(8) Superconductors of an oxygen-defect perovskite crystal structure with a composition expressed by the general formula $(Ba_xM_y)\ Cu_3O_{9-z}$. Here, M = rare-earth metals with Tm as their main element, $x = 1\sim3$, $y = 0.5\sim1.5$, $z = 0\sim3$. $T_c = 60\sim97$ K (63-230524).

(9) Superconducting materials of an oxygen-defect perovskite crystal structure with a composition expressed by the general formula $(Ba_xM_y)\ Cu_3O_{9-z}$. Here, M = rare-earth metals with Er as their main element, $x = 1\sim3$, $y = 0.5\sim1.5$, $z = 0\sim3$. $T_c = 94$ and 95 K (63-230525).

(10) Superconductors of a perovskite crystal structure with a composition expressed by $A_{1\pm x}\ M_{2\pm x}\cdot Cu_3O_y$. Here, A is a combination of Y, La, Lu, Sc, or Yb or Y, and M is a combination of Ba, Sr or Ca or Ba, $0 \leq x \leq 0.5$, y is a number that sufficiently meets the requirement of the valence. $T_c = 77$ K (63-230565).

(11) Superconductors having pinning sites (1-100808).

(12) Black crystal composites with an experimental composition of $Bi_aSr_bCu_cO_d$, $a + b + c = 1$, $a = 0.36\sim0.557$ (especially $0.37\sim0.46$), $b = 0.098\sim0.496$ (especially $0.14\sim0.496$), $c = 0.1\sim0.4$, and d = about $1 + a/2$) that have a transition to superconductivity temperature of above 20 K and that possess the main crystal phase belonging to the orthorhombic system (1-167230).

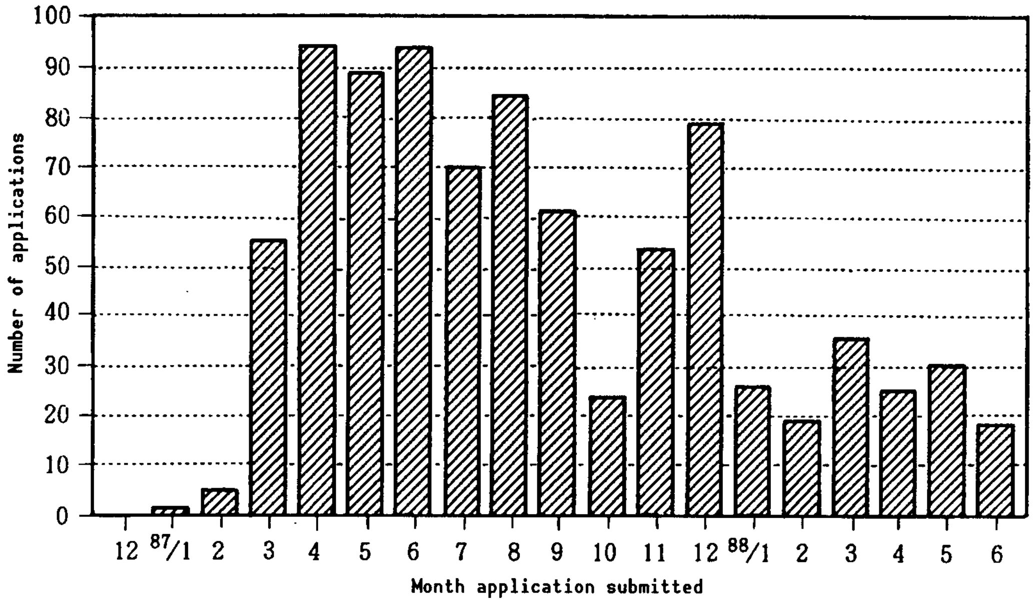


Figure 3.2-4. Applications for Wire Manufacturing Methods

(13) Substances with a composition expressed by the general formula Y_3-X-Ba_x-Cu_y-O_z. Here, x = 0~2, y = 3~6, z = 6~12 (excluding a case where x = 2, y = 3, and z = 6.75~6.97) that latently or actually possess superconductivity at temperatures below the absolute temperature of 95 K and simultaneously possess photoconductivity in the excitation light wavelength region of 420~640 nm at temperatures below 95 K (1-201058).

(14) High-temperature superconducting systems with a composition of TiRBaCuO (R is selected from the IIa family of elements excluding barium) (1-242418).

3.2.2 Manufacturing Methods of Superconducting Materials

Patent applications in connection with the manufacturing methods of wires and films are given in Figures 3.2-4 and 3.2-5.

Both wire and film fabrication techniques are indispensable basic technologies if superconducting materials are to find practical use. A study of the wire-related patent applications shown in Figure 3.2-4 reveals that applications are concentrated in the earlier months, and the reason seems to be that since the technique of pulling bulk into wire is an important key technology, research was energetically promoted during the period. Against it, as can be seen from Figure 3.2-5, the peaks in the patent applications for films are a little bit lagging behind those for wires. When the fact that wire is mainly used in heavy electrical equipment while film is used in consumer electrical and electronic appliances, it is assumed that superconductors were probably designed for use in heavy electrical equipment in the early stages of their development.

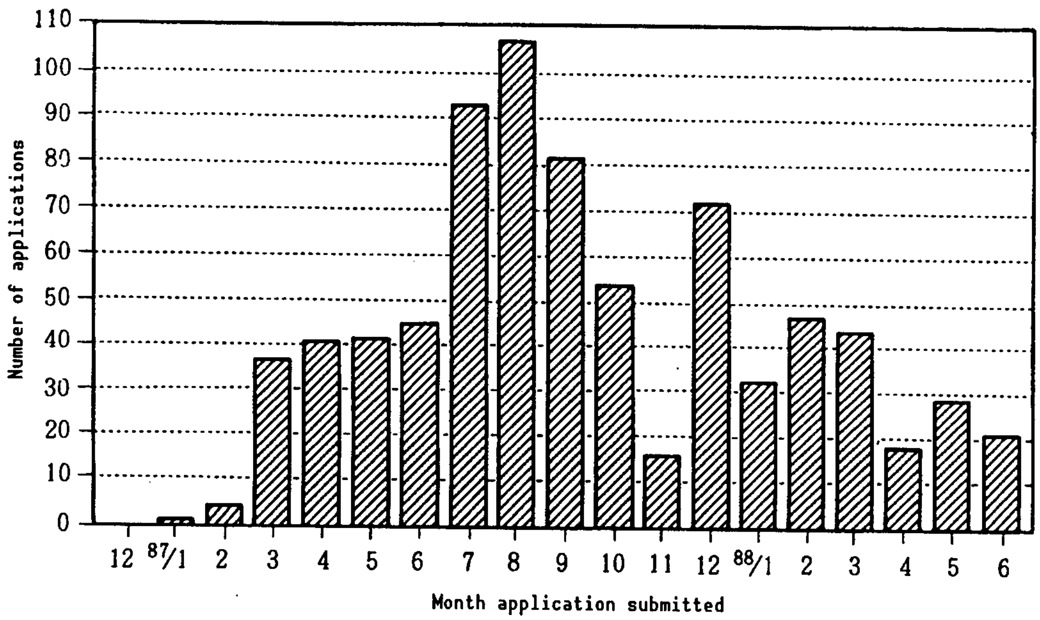


Figure 3.2-5. Applications for Film Manufacturing Methods

(1) Wires

1) Powder of an oxide superconductor is uniformly dispersed in a bath of molten copper or aluminum. After cooling, the ingot is rounded off for fabrication into wire or tape. The digression of surface operation leads the grains of the superconductor to arrange themselves lengthwise, and a superconducting wire is fabricated (63-225410).

2) A drum containing liquid coolant is made to rotate, and a nozzle is installed near the surface of the liquid layer. A molten bath containing ceramic superconducting elements is blasted in a jet onto the liquid layer and cooled rapidly to manufacture a metallic wire-like material. The wire-like material is then shaped into a desired form and is subjected to oxidization processing for fabrication into a superconducting wire (63-231820).

(2) Films

1) An oxide superconductor is deposited on a substrate by sputtering to form a layer of superconducting thin film (63-206462).

2) A coating of a compound oxide is formed by sputtering deposition, thermal deposition, chemical gaseous gas growth methods, etc. (63-224116).

3) Powder of a superconductive compound oxide is added with an organic solvent and is kneaded into a paste. The paste is then screen-printed on a substrate, dried, and sintered to obtain a superconductive thin film (63-232208).

(3) Other Manufacturing Methods

1) La_2O_3, $SrCo_3$, and CuO are mixed and sintered in a preliminary process. The sintered object is then pressed and shaped and is sintered again. It has a composition of $[La_{1-x}Sr_x]_2CuO_{4-y}$ and a layered perovskite structure or similar one (63-218535).

2) Powders of elements making up a layered perovskite compound superconductor are mixed and pressured to form a green compact. The green compact is pulverized into powder, and the powder is again subjected to pressure to form a green compact. The green compact is heat treated. The result is an improved superconductor with an upper critical magnetic field of above 50 T (63-225524).

3) Y_2O_3, $BaCO_3$, and CuO are mixed at a mole ratio of 0.2:0.6:2 and the mixture is formed under pressure, followed by sintering in an oxidizing atmosphere and slow cooling. $[Y_{1-w}Ba_w]_x[CuO_{4-z}]_y$ (63-239113).

4) In this method of manufacturing superconducting materials by sintering, the average grain diameter of the raw material powder is required to be below 1 μm. The raw material is a compound containing at least one of the elements of the IIa family of elements, at least one of the oxygen-containing compound IIIa family of elements, compounds containing oxygen, and compounds containing copper and oxygen (63-239147).

5) Subjecting metal alcoholate to hydrolysis enables an oxide to be obtained. The oxide is suspended to be transformed into a sol. The sol is condensed to be transformed into a gel, which is then heated and sintered (63-248021).

6) In a coprecipitation method, a water solution containing dissolved salts of the constituent elements is added with amines that do not form complexes with copper to shift pH of the water solution onto the basic side, and a weak acid is added that makes the constituent elements coprecipitate (63-252925).

7) A bulk material of metal is cooled to a temperature below its transition temperature to superconductivity, and it is made to move along a magnetic field space to differentiate the travel path of the superconducting oxide from that of the nonsuperconducting substances for separation (63-252273).

8) A magnetic field is applied to fine particles containing dust of a superconductor to make the dust of the superconductor float, and a magnetic field accompanied by a progressive wave is applied (63-252553).

9) Granular substances having different transition temperatures to superconductivity are subjected to an application of a magnetic field at a desired temperature, and the floating superconductive substance is selectively recovered (63-278368).

3.2.3 Applications of Superconductivity

Applications of superconductivity are widely varied, and as many as 3,400 applications have been filed but few of them have been put to practical use. Almost all of these applications are still in the stages of testing. Following are introduced patents in various application fields.

(1) Coils and Magnets

1) A superconducting wire is coated with material like diamond or alumina that has good heat conductivity and is wound to manufacture a superconducting coil with good cooling characteristics (63-192207).

2) A thin film of an oxide ceramic is formed on a substrate by a sputtering method. The thin film does not display superconductivity as it is, but exposing it to laser light triggers recrystallization due to laser annealing, which gives rise to superconductivity. A coil is obtained by patterning in which laser light scans strips of the thin film (63-207009).

3) A pipe wound like a coil is filled with fine particles of a superconductor (63-307708).

4) An oxide superconductor's inside grooves like a concentric circle or spiral on a laminated ceramic board is used as the conductor coil (64-710).

5) A coil is formed by screen printing a paste consisting of powder of an oxide superconductor and an organic binder (64-4004).

6) A coil is formed by winding superconducting wire around a cylindrical core material that burns up in the course of sintering (64-17408).

7) Superconducting material is filled inside coil-like grooves and sintered (64-25507).

8) A coil pattern is formed by photoetching (64-39007).

9) A silver tube is filled with fine particles and is heat-pressed into a pattern of coil (64-59905).

10) A spiral is cut into a cylindrical superconductor to form a coil (64-64303).

(2) Limit Lines, Current Leads

Among electric lines, such as limit lines and current leads, that incorporate superconductivity are the following:

1) A current lead wire that exists between the current supply source that is a complex of a ceramic superconductor and a support made of an insulator or nonmagnetic metal (63-245909).

2) A superconducting power lead, a rod-like device that has terminals of lower resistance metals fabricated on both ends (1-123405).

3) A power transmission method in which, using a superconductor, current is transmitted under a dc voltage of below 1 V per 100 m (63-277424).

4) A superconducting coil manufactured by noninductive winding of a superconductive wire having a large normal conduction resistance and is encased inside a cryostat (63-292611).

5) Current limited by the dc resistance under a state of normal conduction, created by the destruction of a superconductive state (63-4085).

6) Current cut off by forcibly triggering quenching and changing a high-temperature superconductor into an electrical insulator (64-4085).

(3) Generators

Patent applications in generator and related technology are not so numerous but some of them are unique.

1) Superconducting material used in the generator's main bus-line that transmits electrical output from the generator (64-19908).

2) A combined superconducting electric power storage and solar light power generation system (64-19929).

3) The primary power source for satellites (1-114083).

4) An exciting coil made of a superconductive material encased in the vanes of a hydraulic turbine rotor for hydraulic power generation (1-136546).

5) Wave power power-generating equipment incorporating a permanent magnet of room-temperature superconductivity and superconducting coils (1-148054).

6) Of photovoltaic power generation systems that convert solar energy into electric energy using solar cells, those systems that are connected with a protective device having a superconductor arranged in their coil magnetic field (1-164231).

(4) Transformers and Converters

1) A superconducting transformer having a secondary coil that magnetically couples to the superconducting primary coil (1-111314).

2) A method of detecting quenching in a superconducting transformer when electric losses become large (64-89412).

3) A small-loss, large-current transformer in which a coil made of a superconducting material is used as the low-voltage coil and a coil made of a room-temperature conducting material is used as the high-voltage coil (1-15405).

4) An ac/dc converter having a rectifying capability through the adoption of a technique in which the magnetic field of the coil changes the properties of the superconducting material (64-26365).

5) A dc/ac converter in which the two switching circuits are made of superconducting SQUIDs and the critical magnetic fields are applied alternately (1-99479).

6) An analog/digital converter that converts digital signals into analog signals by current characteristics (64-51681).

7) A superconducting analog-to-digital converter in which an input is made into a parametron via an rf-SQUID (1-137727).

8) A frequency converter provided with a superconducting reactor made of superconducting material (1-152962).

(5) Motors

Patent applications in motors number 122, which is very large for superconductivity applications.

1) A damper coil for use in a rotating motor in which the start torque is set by the resistance of the normal conduction section (64-26340).

2) A linear motor in which the adoption of thin films increases the accuracy of progression (64-34171).

3) A motor exploiting a magnetic field generated by an antimagnetic current (64-39262).

4) A voice coil motor that has its size reduced by shielding (4-47251).

5) A single-pole rotary motor that has gained a high-speed rotation due to the adoption of superconducting coils, etc. (64-50745).

6) A superconducting rotating machine of which refrigerating capabilities have been improved by the adoption of a rotator with built-in coils and conduit lines (64-50745).

7) A rotator for use in superconducting rotary motors in which evaporation of the cooling medium prevents the field lead from being excessively heated (64-55056).

8) A rotator having a reinforcing ring that protects the rotor from deformation (64-55060).

9) A superconducting rotator having a superconducting magnetic shield between poles (64-77463).

10) A rotary encoder in which the motor is controlled by incorporating a superconductor in the magnetic rotor (64-88211).

11) A motor in which the number of turns is altered by connecting two points on a coil (1-91691).

12) A superconducting motor in which the take-out section of motive power and the control section of motive power are designed not to come into mechanical contact. [Number not published]

13) A stepper motor having superconductors in the grooves between pole gears (1-126151).

14) An electron governor motor in which the quantity of flow of electricity is governed by comparing it with a reference voltage (1-190282).

15) A superconducting rotary motor equipped with a collector ring for detecting quenching and a sliding brush (1-227656).

16) A superconducting flat motor in which superconducting material is encased and fixed in place in the spiral grooves of a flat board (1-274632).

(6) MRI

Applications of oxide superconductors in MRI number about 30. MRI machines incorporating metallic superconductors have already been commercially developed, and the following are listed applications of oxide superconductors in MRI machines.

1) The use of a superconductor that shows superconductivity at temperatures above the liquid nitrogen temperature for MRI, in which a magnetostatic magnet is used in the MRI equipment (63-281411).

2) Magnet coil equipment for use in NMR cross sectional imaging equipment whose radiation shielding is made up of the second class of high-temperature superconductors (63-31707).

3) NMR cross sectional imaging equipment in which a SQUID sensor is used to detect the echo signal of NMR (63-311945).

4) Magnetic field cross sectional imaging equipment in which supersonic pulses are injected into the subject being examined and changes in the magnetic field of the subject are detected using a SQUID sensor (64-2627).

5) Static magnetic field-generating equipment for MRI, the imaging section of the yoke of which is coated with superconducting material (1-113035).

6) The magnet system for NMR imaging equipment, in which an inclined magnetic coil is elastically supported in the inside cylinder of a soundproof vessel (1-208817).

7) Electron spin resonance equipment incorporating a superconducting cavity resonator (1–216245).

(7) SMES

As for the technology in the field of electric power storage, SMES is representative, and following are listed patent applications in power storage-related technologies.

1) A power storage coil made by winding superconducting wire material around a cylindrical support. Featuring no leakage of magnetic flux outside the equipment, it is a power storage coil that does not affect communications (63–198308).

2) Equipment for the storage of thunderstorm energy that has a loop to include a superconducting coil connected to a lightning arrester, of which the whole structure is made of superconducting material (63–245971).

3) Superconducting power storage equipment, in which a superconducting coil is installed inside a rock cavity, a structural base that insulates the superconducting coil is fixed into the concrete wall inside the cavity, and an airtight shield is applied on the surfaces of the wall except the base (63–269507).

4) A superconducting energy storage facility, a power station, and an existing power grid are combined into a whole and controlled (63–274334).

5) A superconducting power storage system in which high-temperature superconductors are connected in parallel to a superconducting magnet and controlled for temperature simultaneously (63–277435).

6) A combined gas turbine–motor engine that uses a superconducting battery (63–289228).

7) A charger for electric cars that charges by exploiting a magnetic field generating coil while the car is on the road (64–30403).

8) A small-size superconducting energy storage system in which the compression force and expansion force working on the coil are kept in balance (64–32605).

9) A high-rise building provided with superconducting power storage equipment in which surplus electric power is stored in a coil and is discharged when needed (64–61008).

10) A power storage system in which photovoltaic cells and superconducting coils are placed on both sides of a glass (64–73706).

(8) Nuclear Fusion and Reactors

Patent applications in nuclear fusion and reactors are small, and the field is noted for its small number of issued patents.

1) Tokamak nuclear fusion equipment of a structure in which, by exploiting the fact that the superconducting toroidal coil shrinks in the radial direction by the action of electromagnetic force while in use under refrigeration, makes the central column of a material with a linear expansion coefficient higher than that of the coil-supporting frame, results in the coil being fixed into place through refrigeration shrinkage, making it adhere tightly to the central column, which prevents it from distortion (63-184089).

2) Nuclear fusion equipment in which, to prevent invasion of heat into the superconducting coil that occurs in a nuclear fusion system when the superconducting coil and the radiation shield inside the bore come into contact, the coil and shield are kept in a state of electric insulation, and the flow of electricity in the lead wires from the coil and shield is checked, enabling one to know if the coil and shield are in contact or not before the nuclear fusion equipment goes into operation (63-204192).

3) Nuclear fusion equipment with a shell around the high-temperature plasma for stabilizing the superconductor (1-138492).

(9) Josephson Devices

Eight hundred patent applications have been submitted in superconducting devices, including Josephson devices, and this are the largest field of superconductor applications.

1) A four-terminal solid electronic device based on a ceramic superconductor (63-228678).

2) A phototransistor equipped with an optical waveguide for irradiating light of a required wavelength onto a polycrystal superconductor existing between the two electrodes (63-239877).

3) A superconducting read-only memory (ROM) in which memory cells consisting of magnetic and nonmagnetic Josephson devices are made in large quantities on a required pattern and bit information is read out by exploiting whether there is a generation of a voltage or not when a current that is larger than the critical current of the magnetic device but smaller than that of the nonmagnetic device is led to the Josephson device's junction (63-244892).

4) A superconducting device in which the substrate and device proper are made of ceramics (63-245973).

5) A superconducting device that is made by stacking oxide superconductors and semiconductors or constant conductors alternately on a substrate (63-248187).

6) Devices or systems that are based on new superconducting materials. (63-248722).

7) A superconducting laser that generates coherent electromagnetic waves by the work of the crystal grain boundary Josephson effect in oxide superconductors (63-250878).

8) A semiconductor system in which, to protect the semiconductor devices from contamination by metal atoms of the superconducting wiring material, the wiring circuitry is prepared separately and connected to the semiconductor circuit elements (63-260062).

9) A Josephson junction device that has its superconducting section and weak connection section made of oxide superconductors and in which the critical temperature of the superconducting section is higher than that of the weak connection section (63-269585).

10) A Faraday device in which superconducting material is placed around the optical waveguide to control the light polarizing plane inside the optical waveguide (63-291029).

11) An elastic surface-wave device in which a superconducting fluted electrode having conversion capabilities between electric signals and elastic surface waves is installed on a piezoelectric substrate (63-292715).

12) A light emitting device that has a light-emitting section made up of a superconductor as well as means to pump electronics and holes into the light-emitting section (63-302581).

13) A superconducting three-terminal device made up of two tunneling junctions (63-305573).

14) An optical integrated circuit in which the active element section is inserted inside the superconducting traveling-wave-line section (64-7007).

15) A magnetic memory device in which the direction of magnetization inside a pattern formed by ferromagnetic film is used as the unit of information (64-10486).

16) An optomagnetic device made of waveguides stacked up on a superconductor (64-10679).

17) A Josephson device incorporating an oxide superconductor that creates more than three switching states by exploiting magnetic field, electric field, and light (64-11376).

18) An optical switch that controls the light sensitivity by P-N junctions (64-50486).

19) A superconducting optical memory device in which rewrite is initiated by optically controlling the permanent current (64-51678).

20) A low carrier-density superconducting three-terminal device having a ring section that generates quantum interference between input and output powers (64-89478).

21) A magnetic memory device that enables high-level memorization by letting the first and second superconducting wires form a ring encircling the magnetic film and the second wire at the intersection (1-92996).

22) A noise-removal device in which superconducting thin films and dielectric films are stacked up one on top of another (1-140618).

23) A superconducting Schottky gate electrolytic-effect transistor in which the gate electrode has a two-layer structure of a compound oxide superconductor and Au (1-146372).

24) A magnetic flux quantum device in which one of the J-line branching sections is resistance connected and the other is looped (1-173676).

25) A superconducting diode in which two semiconductor layers are built using a superconductor inserted between them (1-173767).

26) A pressure gate-type transistor incorporating a superconducting material (1-183860).

27) A superconducting parallel processor equipped with superconducting channels arrayed in a matrix (1-187666).

28) A bipolar semiconductor system in which the emitter is made from a superconducting ceramic (1-196869).

29) A superstructure high-temperature superconducting material that is made by stacking oxide superconductors and metallic superconductors alternately (1-215074).

30) A magnetic substance-semiconductor lamination in which superconducting properties are generated when electron spins of the magnetic substance join through the electrons of the semiconductor (1-217979).

31) A superconductor-base transistor in which layers of atoms of substances with a superconducting composition are deposited on the surface of the semiconductor layer in the collector region (1-303770).

(10) Switches

1) A pushbutton switch in which the open state of switch is formed by the Meissner effect (63-318029).

2) A superconducting switch in which current is cut off by magnetic cutoff in a superconducting state (64-27138).

3) A permanent current switch in which the direction of a current is changed using two coils (64-48332).

4) A sealed lead switch in which current flowing through a superconductor is cut off by an external magnetic field (64-48332).

5) A fuse bound to a superconductor that melts in a shorter period of time (1-122540).

6) A microooptical switch incorporating superconducting magnet and a magneto-optical crystal (1-133024).

7) A keep relay in which the moving iron is retained by the magnetic force of a superconducting coil (1-189830).

8) An off-delay relay that has a yoke conductive part provided with a superconducting coil and a lead piece (1-194219).

(11) Wiring

1) Interconnections of a resistive thin film and interconnections of a superconductive thin film are formed in an overlay across the entire area and the superconducting film is removed from where resistance elements are needed, to leave behind only the interconnections of the resistive film (63-169082).

2) To raise the thermal conductivity of the interlevel dielectric used in superconducting circuit equipment, Si film of a diamond crystal structure, SiC film of a zinc blend crystal structure, or AlN film of a wurtz crystal structure is used (63-209185).

3) A circuit pattern is formed by shining a heating beam at a layer of superconducting material along the track of the intended current circuit and heating the layer (63-273371).

4) A layer of an oxide superconductor is formed on the surface of a semiconductor device and those areas of the surface other than interconnections are rendered nonsuperconducting by ion implantation (63-291436).

5) A circuit pattern is formed by melt-depositing superconducting material on a ceramic substrate (63-299193).

6) A paste containing superconducting material is printed on a substrate and sintered (63-300591).

7) An oxide sintered body is adhered to a support and is ground into a thin plate. Then, those areas other than interconnections are removed from the thin plate (63-310197).

8) A multilayer of dielectric material is made on a superconducting pattern and is stripped in a lift-off (1-120892). Among other applications are: a conducive paste made by dispersing powder of an oxide superconductor in a vehicle (63-250025); a method of vapor deposition that causes no deterioration due to the use of Joule heat (64-27173); and an increased strength through the use of soldering material of active metals (64-28284).

(12) Antennas

1) A coating of an oxide superconductor is applied to the surface of an antenna to exploit the effect that the lack of skin resistance of the superconductor enables the antenna to lose little power (64-17503).

2) A microstrip and a feeder of superconducting materials are applied to a flat-faced antenna (1-137805).

Superconducting antennas will, of course, become practical if materials that superconduct at room temperature are developed, but depending on what purpose they are used for, such antennas may become feasible even if they need refrigeration at liquid nitrogen temperature.

(13) CRTs

1) Equipping device with a polarized yoke using a superconducting wire material for a high-resolution Braun tube (63-264851); a device in which the external magnetism is cut off by the Meissner effect (64-30144).

2) Filling the spaces between phosphors in the shadow mask type color television picture tube with superconducting material (1-140539).

3) Depositing thin films of superconducting material so that they encircle the electron beam passage holes formed on the shadow mask plate (1-154437).

(14) Other Electric Appliances

1) A waveguide-type oscillator in which the inside surface of a metallic cylinder of a high heat conductivity is lined with thin films of a YBaCuO oxide superconductor (63-296501).

2) Prevention of current loss by making the interior surface superconducting (64-78502).

3) A superconducting signal line consisting of a lengthwise magnetism generating source and magnetic field receiving section that is encased in a superconducting tube (1-109498).

4) An oscillator in which the magnet shuttles between superconducting materials at a fixed cycle (1-123509).

5) A radio communication technique in which an approaching mobile object makes the superconducting wire change its state, which emits radio waves (1-13228).

6) A multilayer condenser that has its internal electrodes made of oxide high-temperature superconducting material (1-161940).

7) An information exchange system in which modulated waves are output to a superconducting material to make them pass through a wave filter (1-161940).

8) A microwave dielectric resonator in which the tip of the post for adjusting the bonding strength is formed of a superconductor (1-170102).

9) An electron gun whose electrodes are formed of superconducting material (1-186540).

10) A high-frequency filter in which the superconducting coil inductance and capacitance are connected in series (1-293005).

(15) Imaging Technology in Copying Machines

1) Exposing the surface of an antimagnetic sensitive material made of oxide superconducting material and locally magnetizing it produced an image (63-291077).

2) Raising the temperature of a superconducting photosensitive drum to a level above its T_c makes it dielectric, and this enables a latent image to be formed (64-15745).

3) The conductive electrodes on the back of an electrophotographic sensitive material are made of a superconducting material (64-38756).

4) By giving a heat pattern to a superconducting sensitive material, an image is developed under a magnetic field (64-78276).

5) The surface of a liquid crystal panel box is implanted with superconducting fibers (1-99290).

6) A superconducting screen is installed over a liquid panel surface (1-113786).

7) Writing is done in the magnetic field by sealed cells arrayed in a matrix with a combination of superconductor and soft magnetic material (1-167788).

(16) Magnetic Heads

Patent applications in magnetic head-related technology are numerous, numbering some 160, but many of them share similar features.

1) The magnetic head is floated above the recording medium by using oxide superconductors in some sections of the support (63-249983).

2) The peripheries of the magnetic circuit are covered with a nonmetallic superconductor (63-253509).

3) A ring-type magnetic head whose magnetic gap consists of a ceramic superconductor (63-259813).

4) Vertical recording by temporarily breaking the superconductive state (64-37702).

5) A magnetic tape featuring a superconducting film with the Meissner effect is levitated from the head (64-48203).

6) A configuration in which a SQUID is formed inside the magnetic core and the magnetic flux generated inside the magnetic core is made to pierce through the SQUID (64-49105).

(17) Recorders

The recording technology is one of the areas where patent applications are numerous, numbering 120. When the magnetic head-related applications are also counted, the total comes close to 300.

1) The magnetic substance coated with a magnetic shielding material made up of superconductors on a magnetic recording medium. [Number not published]

2) The recording medium as a photoelectromagnetic recording medium (63-244410).

3) A configuration having a recording layer where information is recorded as the direction of magnetic momentum of a light spot and a superconducting layer established adjacent to the recording layer (64-4944).

4) Magnetic recording protected using a superconductor (64-34201).

5) Vertical recording in high densities by the invasion of the magnetic flux (64-33750).

6) High-speed recording by fixing in place the trap magnetic flux (64-49660).

7) A superconductive magnetic tape that enables vertical recording in densities of triangular lattices among magnetic flux to be obtained (64-50231).

8) A magnetic recording film in which the magnetic flux is made effective by coating its back with a superconducting layer (64-53336).

9) The recording medium made to float by the Meissner effect to let it rotate without contacting anything (64-67783).

10) Recording obtained by raising the temperature and erasing the superconducting current (64-72345).

11) Magnetic recording obtained when the heating mesh-like pattern is refrigerated at a level below T_c (1-136759).

12) A multivalued magnetic recording and reproducing system in which a recording is obtained, using laser light that varies in intensity, on a multilayer recording layer that has superconductive films with different critical temperatures sandwiched between magnetic layers (1-258204).

(18) Lighting Apparatuses

1) In the lighting circuit of a fluorescent electric discharge lamp, room-temperature superconductors and coils connected in series electrically and the superconductors and fluorescent electric discharge lamp connected in parallel electrically (64-695).

2) Light emitted by using a superconductor and applying a high-frequency electromagnetic field (1-95494).

3) A lighting system of an electric discharge lamp that uses a stabilizer with its core made of superconducting material (1-144596).

4) A speaker that is free from magnetic leakage due to magnetic shielding (64-69199).

5) A speaker that has a magnetic reflecting plate made of superconducting material (1-114199).

6) A headphone with a vibration film made of superconducting tape (1-114200).

7) A superconducting speaker box that has its interior surface lined with a superconducting thin film (1-129598).

8) Superconducting biofeedback equipment in which bioreactions are generated as acoustic or image output (1-130975).

(19) Optical Technology

1) Light that is shined at a superconducting substance and the intensity or spectrum of the light extracted altered based on the transition from superconductivity to normal conductivity for use in an optical shutter or an optical write head (63-291027).

2) A semiconductor laser system that has a smaller spectral line width due to the use of a superconducting coil (64-68994).

3) An optoisolator in which light is polarized by the magnetic force of superconducting rings on a thin film crystal (64-90412).

4) A reduction projection optics system using an X-ray light source, which incorporates superconductors of a single crystal structure (1-102399).

5) An optical modulator with a progressive wave-type of directional coupler that incorporates superconducting electrodes (1-102435).

6) A display system in which phosphor emissions of light are controlled superconducting magnets (1-112645).

7) An optical modulator with a magnetooptical crystal that has magnetic fields applied using a superconductor (1-133025).

8) A liquid crystal display system that has electrodes of superconducting films for its liquid crystal drive electrodes (1-133034).

9) A laser system that incorporates superconducting mirrors (1-140785).

10) A light-emitting device that has the surfaces of both sides of its EL-emitting layer lined with a layer of superconducting material (1-157092).

11) A pulse power laser in which switching is conducted by destroying the state of superconductivity, using a circuit current magnetic field (1-206679).

12) An optical attenuator with a conductive pattern of a superconductor in a soft magnetic substance layer in an optical waveguide (1-282518).

(20) Printers

1) An ink jet printer in which ink having powder of a superconductor mixed in it is injected from a nozzle provided with an electromagnetic coil (64-4354).

2) A magnetic ink recording head in which, depending on the signal, the magnetic flux shielding is made nonsuperconducting in order to inject ink (64-80545).

3) A superconducting coil used in the drive coil of the printing head in a wire dot printer (1-180355).

(21) Applications of Superconductors in Means of Heating

1) A superconducting scalpel in which tissues are coagulated and excised by using Joule heat that is generated when a transition to a state of normal conductivity occurs (63-272341).

2) The coil for high-frequency magnetic field heating in an electromagnetic hot water supply system is made of a superconductor (63-308889).

3) Heat energy taken out by destroying superconductivity (1-287975).

(22) Use of the Meissner Effect

1) A centrifuge in which the separation tank is made to float by the Meissner effect (63-302969).

2) An antenna that retains its directionality due to a floating magnet (64-30303).

3) A magnetic disk that is kept floating by the action of the Meissner effect (64-39677).

4) An ink-jet head whose ink does not come into contact with it because of the Meissner effect (64-40343).

5) A powerful repulsive force obtained by a permanent current (64-46030).

6) The surface of a resist coating planarized by the Meissner effect (60-59422).

7) A heat engine in which the Meissner energy provides its rotary energy (64-50774).

8) The mechanism of a low friction in which a magnet keeps a superconducting rotor floated (64-61608).

9) The repulsive force generated by the Meissner effect works on the car and buffer stop (64-75782); a magnetic floating vibration-proofing mechanism that incorporates superconductors and magnets (1-139488).

10) A magnet that keeps an ice-making plate lined with a superconducting material at its underside floating (1-150771).

11) Measurement of the Meissner displacement to enable a high-precision measurement of weight (1-202627).

12) The position of a circling satellite controlled by detecting the geomagnetism working on the satellite using the Meissner effect (1-285497).

(23) Other Applications of the Mechanisms of Superconductivity

1) A damper that exploits the Lorentz' force between the eddy current and magnet for its damping strength (63-312536).

2) A microdrive system in which a position-to-position shift is obtained by shining light at a piece of magnet and raising it to a temperature above its critical temperature (64-16278).

3) An injection molding machine of synthetic resin that is driven by superconducting magnets (64-18618).

4) A superconducting pump in which the liquid flows due to the vertical forces of the electric current and magnetic field (64-26358).

5) A high-temperature superconducting electromagnetic clutch in which a superconducting magnet is placed on the torque transfer plane (64-26361).

6) An electromagnetic actuator in which a high torque is obtained by reducing the leakage of the magnetic flux (64-50748).

7) A drive mechanism in which the change from a superconducting to a nonsuperconducting state enables the magnet piston to reciprocate (64-87879).

8) A system in which a plate superconductor repulses against an electromagnetic coil, thereby making it reciprocate (1-95423).

9) A pump in which a traveling magnetic field is applied on a rubber-like pipe containing superconductors (1-96481).

10) A motive power-generating system in which a magnet travels at high speed when the superconducting base is shined with laser light and is turned into a normal conducting state (1-114380).

11) A multiaxis output system in which the generation of a water current inside a circular pipe by the action of electromagnetic force enables an impeller connected to the drive shaft to rotate (1-126153).

12) An ice maker in which a current of water is generated by the Lorentz force (1-139979).

13) A superconducting fan in which the gas from an ionized gas generator is sent by a magnetic field (1-190255).

14) An automatic switchover valve in which a cylindrical superconductor is inserted inside the valve of a feeder (1-193471).

15) A seawater pump in which a superconducting magnet enables a magnetic field to be generated inside a cylindrical conductor placed under water (1-268450).

16) A mechanism for controlling the actuator current by the hall voltage of an isotropic superconductor (1-298989).

(24) Magnetic Bearings

More than 40 patent applications have been filed in bearings from the applicants' hope that magnetic bearings may find practical use.

1) A bearing that is kept from contact by the action of the Meissner effect (1-261512).

2) A rotary or reciprocating axis formed of magnetic or superconducting material, and the bearing that supports the axis formed of superconducting material (63-243523).

3) A bearing that consists of a ring- or vase-shaped permanent magnet and a cylindrical high-temperature superconductor (63-251624).

4) A bearing in which the current value of the bearing coil is controlled by displacement sensors (1-141222).

(25) Magnetic Circuits

Most of the patent applications in magnetic circuits are in those that exploit the Meissner effect.

1) Coating the magnetic wire core with a superconducting layer enables the magnetic flux to be transmitted long distances (63-255904).

(26) Patent Applications of Oxide Superconductors Pertaining to Environments

1) An environment that is equipped with a means to remove moisture from the casting (64-18902).

2) A deoxidizer is placed in a vessel to prevent an accumulation of oxygen from exploding (64-25489).

3) T_c is maintained constant in an oxygen atmosphere (64-50316).

4) A superconductor is sealed to a desorption element (64-64305).

5) A state of superconductivity is controlled within the temperature limits by detecting the temperature (64-89475).

6) The performance is maintained by treating the environment with ozone of high densities (1-203202).

(27) Shielding Technology

1) A superconducting magnetic insulator made of a layer of superconducting films and a substrate with a large number of small holes (63-233577).

2) A compound radio wave absorber made of an absorbing layer containing dielectric absorbers and magnetic absorbers and a reflecting layer in a state of thermal conduction laminated together (63-136900).

3) A magnetic shield made of a ceramic superconducting material (63-280470).

4) A magnetic insulating material that has a granular oxide superconducting material and a fibrous material deposited on a substrate (63-291313).

5) A compound superconducting magnetic insulating material in which a superconducting filler of powder, thin chips, or fibers is mixed throughout an organic matrix (63-313900).

6) A shielded room in which the field strength of electromagnetic energy is reduced to zero by shielding it with thin films (64-39799).

7) Fibers coated with a superconductor that is used as an insulating material (64-82697).

8) An analog electronic watch that is free from the effect of external magnetic fields due to its incorporation of a superconducting material on the surface of its armor (1-96587).

9) A magnetic encoder in which a superconducting material is used for magnetic shielding (1-145519).

10) An electrode shielding structure for electric appliances in a building in which the exterior of the building is coated with a superconductor (1-230300).

11) A superconducting magnetic insulating vessel of a structure in which strips of a substance with higher T_c are alternated with those of a substance with lower T_c (1-274498).

12) A temperature-sensitive switch in which switching is controlled by the magnetic shielding effect of a superconductor (1-276526).

(28) Transportation Equipment

1) Superconducting coils arranged vertically on the sides of a chassis of a magnetically levitated train of a magnetically repulsing structure, and coils for propulsion installed on the side wall of a U-shaped guideway. Furthermore, a coil array for a magnetically levitated train in which the top and bottom coils for float that are connected opposite to each other to form a closed circuit, are installed on the surface of a coil for propulsion symmetrically to the center of the propulsion coil (63-167606).

2) A superconducting drive system featuring a double-reversal propeller in which generating a magnetic field using a superconducting coil to give axial-direction currents, which are in opposite directions to each other, to the inside and outside rotors gives rise to the generation of circular electromagnetic forces of reverse directions on each of the rotors, which makes the front and rear propellers rotate in opposite directions (63-217968).

3) A repulsive firing system; in a firing system provided with a formed cylinder and a superhard insulator—it is encased inside the formed cylinder and keeps in place the conduction coils; it is the material of which the firing bore is made—in which a projectile is placed in the firing bore of the superhard insulator, the projectile is equipped with secondary induction coils and a cooling medium, and is accelerated by the repulsive force of the induction coils and the jetting pressure of the coolant in order to be fired (63-238399).

4) A ship using electromagnetic force for its propulsion in which the interaction between a magnetic field in the seawater generated by an electromagnet on board the ship and a seawater current from an electrode on the ship's hull generates a thrust (63-247196).

5) An electromagnetic firing system in which the feeder rail is a thin, superconducting feeder rail made of a high-temperature superconducting material (63-251799).

6) A device for giving a lift to a wing which, when a winged object with an azimuth angle moves through an electrically conductive fluid (such as seawater, mercury, plasma, liquid metals, ionosphere air), an electromagnetic force works on the negative pressure surface of the wing (63-258287).

7) A magnetically levitated toy in which high-temperature superconductors and magnets arrayed opposite to each other generate repulsive force, which enables one of the two to float and slide (63-275358).

8) A brake for vehicles in which the repulsive force from superconducting magnets installed at the front and rear sections of a car prevents the car from bumping into an object (63-277401).

9) An electrical propulsion system in which braking energy is stored in a superconducting coil (63-305705).

10) A magnetically levitated system in which a nonuniform array of magnetic poles generates the Meissner effect, giving it an increased buoyancy (63-310304).

11) A missile firing system in which a large number of pulse coils are excited in sequence (64-23098).

12) A system in which the driving force is obtained by temperature differences due to the Meissner effect (64-24474).

13) A shock absorber for elevators in which an elevator is protected from a collision by exploiting the repulsive forces of electromagnetics (64-48789).

14) A current velocity accelerator for use on rivers and at sea, in which the flow of a water current is accelerated by using magnetic force to wash away trash (64-62506).

15) A linear electromagnetic actuator in which feeding a current enables a superconductive object to be transferred in its axial direction (64-64551).

16) A magnetic carrier in which an object is hoisted without contact by the suction force of a coil (64-69494).

17) A contact-prevention system in which the guardrail and cart are protected from coming into contact by exploiting the Meissner effect (64-69494).

18) An electromagnetic propulsion ship provided with a rotatable and movable electrode that emits an electric current intersecting a magnetic field (1-119498).

19) An ac electromagnetic propulsion system in which a fluid is pushed forward in the same direction by a half-wave rectification current (1-182194).

20) An automobile safety device that senses a shock by exploiting super-conducting clothing and a coil embedded inside the steering wheel (1-215656).

21) Dredging equipment that is provided with a superconducting coil for magnetic fields and an electrode that feeds current in the direction in which sand and mud are being carried (1-239232).

(29) Other Applications

1) Of the technology of separating oxygen in which a gas containing oxygen molecules is supplied from the supply side to an oxygen separation film, and oxygen is separated by keeping the infiltration side of the oxygen separation film in a state of reduced pressure, an oxygen separation process in which a superconducting magnet is placed near the infiltration side of an oxygen separation film and a magnetic field is applied to a gas containing oxygen to isolate oxygen from the gas (63-242319).

2) Liquid oxygen separation equipment in which liquid oxygen is separated from a liquid gas by applying a magnetic field to the gas and making the oxygen polarize (63-264155).

3) A teaching materials kit that consists of superconductors of various shapes and permanent magnets (63-282774).

4) A heatproof film for electronic ovens which, covered with thermal thin film, is free from temperature increases (1-93345).

5) A plate for lead batteries, which is made by filling the hollow section of a steel column-shaped body with superconducting material (1-105476).

6) A method of removing dust sticking on a filter using a magnetic field (1-143617).

3.2.4 Refrigeration Technology

Refrigeration technology is applicable to both oxide and nonoxide superconductors, and drawing a clear distinction between the two types of superconductors is impossible.

(1) Pressure-retaining equipment in which an electromagnetic valve and a check valve that opens at pressures above a certain value are installed in series at the passage of helium gas from a liquid helium container to keep the pressure inside the helium container constant, and the liquid helium is taken out as needed (63-161604).

(2) A strap-on type refrigeration system for cryogenic computers, which features a simple structure and nonuse of a liquefied gas. It is made by combining a cooling plate of copper or aluminum that has a built-in passage of the gas whose temperature has been lowered as a result of an adiabatic expansion and a ceramic substrate embedded with semiconductor devices together in a way that an exchange of heat will take place between the two (63-181385).

(3) A cryogenic container of which the inner cylinder is made of a lamination of alumina fibers. It features a higher heat conductivity than a similar container of glass-reinforced plastic. The result is that even if a cryogenic cooling medium is poured into the inner cylinder at high speeds, large temperature gradients will not occur on the inner cylinder, thereby making it free of cracks (63-213906).

(4) To reduce the pulsating sound that is generated when gas flows through a refrigerator, a pipe free of cavities on its inner surface to pipe at the inlet and outlet port of the cooling gas of the radiation shielding for the superconducting magnet (63-217608).

(5) A low-temperature container made of a heat-shielding plate, a metal plate of good heat conductivity, such as copper, that is coated with a thin film of highly-heat conductive diamond (63-220505).

(6) A refrigerating system of which the cooler is a "Verchae" device (63-266888).

(7) A configuration in which two sets of heat exchanger are placed inside liquid nitrogen, one at the top and the other at the bottom, and the temperature of the upper set of heat exchanger is lower than that of the lower set of heat exchanger (63-299181).

(8) A cooling cable in which superconducting ceramic inner and outer pipes with a cooling path running through their interior are alternately arrayed in large numbers (63-313419).

(9) A cooling vessel provided with a moisture remover (64-19619).

(10) A multilayer insulating material in which the rate of infrared radiation is reduced by the use of superconductors (64-49632).

(11) A low-temperature vessel for superconducting magnets in which generation of an eddy current is prevented by building a heat-shielding plate of a multilayered structure (64-84054).

(12) A cryogenic refrigeration system in which impurity gas is removed at a temperature at which it does not solidify, using an absorber (64-84054).

(13) A semiconductor package refrigeration structure in which terminals are bonded to a laminated board through coolant throughholes (64-86543).

(14) A kitchen system in which a cooling medium is supplied to low-temperature superconducting electrical kitchen utensils (64-8803).

(15) An antifreeze device in which, when the temperature of a superconducting valve drops to a certain point, it floats by the action of superconductors around the drain hole (1-108481).

(16) A refrigeration system for computers in which refrigerant gas vaporized in a sealed vessel is again turned into liquid for reuse (1-137680).

(17) An He refrigerator incorporating a low-temperature check valve that enables gas to flow in opposite directions (1-139959).

It is impossible to list all 7,400 patent applications in oxide superconductors that have so far been filed, and those listed above are some of the major technologies.

Chapter 4. Post-Survey Findings

The Second Committee convened a panel discussion on a topic entitled "Findings of a Three-Year Survey," and outlines of the discussion are listed below.

4.1 Current State of Superconductor Development

When high-temperature oxide superconductors were discovered three years ago, there was an apprehension that superconductors with lower carrier densities like oxide superconductors would not be able to carry large currents. (The majority opinion was that oxide superconductors had attractive properties but putting them to practical use would be difficult.)

The past two years have witnessed a successive stream of announcements of oxide superconductors having higher critical current values, but strong reservations have been voiced, especially in the United States, about a problem that a finite resistance appears in oxide superconductors through which a current is flowing. However, as Champion Data indicates, recently data showing conduction of large currents through neutron-irradiated samples at liquid nitrogen temperature have been presented in the United States, and solution of the problem theoretically is being viewed as promising.

A problem currently facing the technology is largely an issue of materials technology—how to fabricate long-size wire out of brittle ceramics that will have a structure suitable for carrying large-current densities.

4.2 Prospects of Superconductors

(1) Technical Forecast

1) Technical forecasts will have to be made with the following fact in mind: that technical innovations may not necessarily come from people in the specialized field but may be achieved by people in some unrelated fields (an answer to the presentation that experts tend to see the potential of a technical innovation with more pessimism).

2) SMES is a high target in the field of electric power. A breakthrough may come from some unrelated idea, but because of the many technical tasks it will take a long time before the technology will be put to practical use. Superconducting transmission cable that does not require a ferromagnetic field may be easier to realize.

3) In Japan research and development is scarcely being done on the high-frequency devices that are expected to hit the market ahead of others, so research of the technology will have to be promoted as a cooperative project.

(2) Market Scale

Once developed, three-terminal devices will find application in various fields. The market for three-terminal devices based on oxide superconductors is expected to be large.

4.3 How To Promote R&D of Superconductors

(1) In a long-term task like research into superconductivity, the chance of success seems to be high if the effort optimistically aims at a higher goal.

A method will be to set a target date to realize SMES based on oxide superconductors. In the energy field it will be necessary to appeal to the public the social needs of superconductivity.

(2) An international competition in superconductivity R&D may also be a method of promoting the technology.

(3) Since the principles and characteristics of superconductivity are too difficult to understand, it will be necessary to devise design tools (such as manuals) that are easy for electronics engineers to use. The number of researchers in this field (device physics) is too small.

(4) R&D will have to be promoted under close cooperation between systems, materials, and physics engineers.

(5) Materials development will not progress unless the people concerned commit themselves to the enterprise with high hopes.

4.4 Commercial Applications

(1) It may be quite all right to aim at a grandiose project, but in reality it is advisable to undertake commercialization of a simple application that requires refrigeration by liquid nitrogen.

(2) Since superconductivity has a broad application, it is advisable not to confine its use in such consumer products as cameras and video equipment but to search for its use in a broad range of applications, such as the peripheral technology to utilize space and sphere at great depths of ground. It may also be a good idea to explore if the superconducting wires at their current levels of technical development have any chance of commercialization.

(3) Technical development should first target itself to commercialization of small items like devices for sensors and magnetic shields.

(4) In the application of oxide superconductors, the first approach should be directed toward objects with simple specifications like magnetically levitated trains and accelerators.

(5) Since SMES has a design problem with the precaution against quenching, it is advisable to first manufacture an experimental product and conduct its verification test before starting its commercial production.

(6) In the case of application of superconducting magnets to magnetically levitated trains, it is advisable to first develop a practical use magnet and use it in practice. (For example, one car of a 14-car train is a car incorporating oxide superconductors.)

(7) Japanese big enterprises tend to set their sights on something big, but they are advised to make efforts to apply superconductivity to something small and simple, such as magnet bearings.

4.5 A Change in Concept

In oxide superconductors, there is a gap between "available technology" and "usable technology." Since thin films belong to the "available technology," there is a potential for the development of a small magnet based on thin films, thereby transforming the technology from "available to usable technology." A rational approach would be to make an effort for a scaled-up version of the magnet. A technical innovation may also be realized by engineers in the field of devices when they ponder the possibility of applying those devices in energy-related use.

4.6 Role of Japan

Japan and the United States now lead the world. Japan should be a good rival of the United States, competing fiercely in the true meaning of the word. Only rivals can cooperate truly. At present, none of us is fully armed with a theoretical concept of how to pursue a strategy for technical innovation. As was the case with the United States in which the country cheerfully led the world in basic research, Japan will now be required to set its long-term perspective on harmonious coexistence with the other nations, including in the field of superconductivity development.

In the field of electric power, the warming of the globe, brought about by burning fossil fuels, is becoming a big problem. Consequently, expectation is placed on superconductivity technology in such fields as energy savings and development of new energy sources (especially, photovoltaic power generation).

Postscript

This survey was conducted for three years beginning in FY 87, and the survey reports are put together by fiscal year. As an official survey on high-temperature superconducting materials, this survey, we believe, was undertaken at a most opportune time.

The research and development activity on high-temperature superconductors for the past three years has really been hectic, and because of the big news that popped up, we had to occasionally rewrite all our manuscripts in the course of putting together the survey reports that we received. In the initial stages of the development of superconducting materials, the corporate expectations that those new materials may find ready applications sent a large number of companies scrambling for research and development lest they be left behind the competition. Three years later, as was the case with development of a large number of new materials, as consciousness has taken root among the companies that it will be a long time before the high-temperature superconductors find practical use. With this realization, a sanity, it seems, has returned to research and development. The greatest task in the field of application of superconductors in electric power is developing long wire that maintains its

high performance. The one greatest task in the field of electronics is developing good thin films and establishing the technology to process thin films into devices.

Given the large impact that practical use superconductors will have on industrial society, research and development is still being promoted on a gigantic scale today, three years after the first discovery of an oxide superconductor. On the other hand, the changes in the economic and technical environment of the world in the past three years have brought about a big change in the manner of R&D that Japan should pursue, and a big emphasis has come to be placed on rendering assistance to the seeds of science and technology for the next generation. The superconductivity technology, ranging from applications of metallic superconductors to practical use of high-temperature oxide superconductors, is expected to become one of the key elements in science and technology in the 21st century, giving a dream for the promising future of science and technology.

Results of this survey forecast that many years of research and development will still be needed, and this conversely suggests that the industrial technology of superconductivity will become a model case for the private-government cooperative relationship in a new international situation. In concluding the three years' survey activity, we pray for a healthy growth of industrial technology of superconductivity that harbors a great potential for playing a big role in the coexistence between the earth and humankind, by contributing to savings in resources and energy.

– END –